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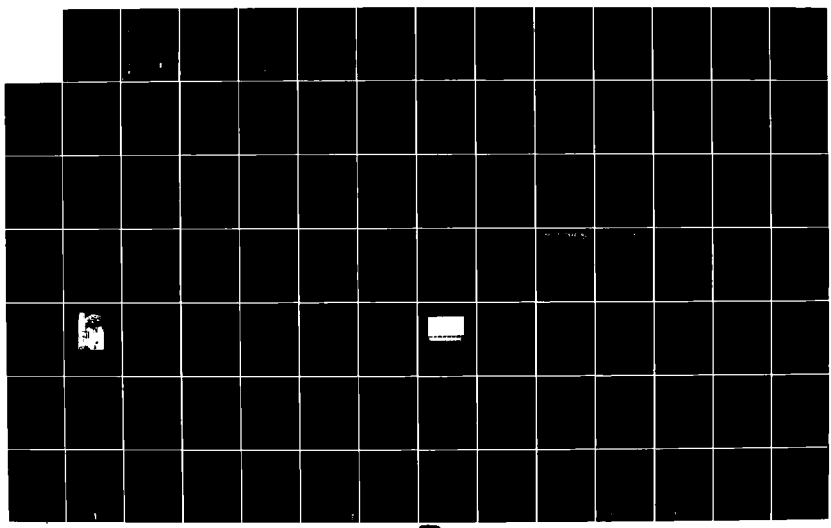
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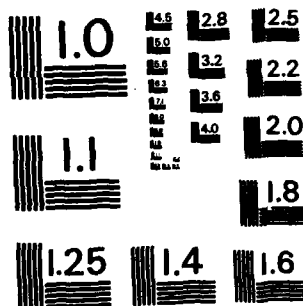
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THE SALT-GRADIENT SOLAR POND

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This technical report has been reviewed and is approved for publication.

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ABSTRACT

The salt-gradient solar pond was modelled both experimentally and numerically. The experimental model used a small-scale tank with artificial sunlight. Both temperature and concentration measurements were taken. The numerical model used a one dimensional heat conduction model to describe the heating phenomena in the pond.

The two models predicted the same type of behavior as that expected in full-scale ponds. There were small differences in the two models. These differences arose from simplifications in the numerical model.

LIST OF SYMBOLS

h	distance below surface (positive downwards) [=] m
h_1	depth of the UCZ [=] m
k	thermal conductivity of the pond solution [=] W/m°C
n	refractive index of pond solution (non-dimensional)
q	salt concentration [=] kg/m ³
t	time [=] sec
C_p	heat capacity of pond solution [=] J/kg°C
D	depth of the combined UCZ and NCZ [=] m
D_s	depth of the LCZ [=] m
F	fraction of radiation which is absorbed in a small distance, δ , of solution (non-dimensional)
I_h	irradiance at a given pond depth [=] W/m ²
I_s	irradiance just beneath the pond surface [=] W/m ²
m	mass of pond [=] kg
Q_D	rate of energy transfer to load [=] J/m ²
Q_{LG}	rate of energy transfer to ground [=] J/m ²
Q_{LS}	rate of energy loss through the surface [=] J/m ²
S	pond surface area [=] m ²
T	temperature in the NCZ [=] °C
T_0	reference temperature [=] °C
T_a	ambient temperature [=] °C
T_b	temperature in the LCZ [=] °C
T_s	temperature in the UCZ [=] °C
U_{LG}	heat transfer coefficient at the pond bottom [=] W/m ² °C
U_{LS}	heat transfer coefficient at the surface [=] W/m ² °C
Z	dimensionless distance in the NCZ

α	thermal diffusivity of the pond solution [=] m^2/sec
δ	small distance in which the fraction F is absorbed [=] m
θ	dimensionless temperature in the NCZ = T/T_0
θ_a	ambient temperature in dimensionless form
θ_b	dimensionless temperature in the LCZ
θ_{GW}	ground temperature in dimensionless form
θ_r	refracted angle [=] radians
θ_s	dimensionless temperature in the UCZ
θ_z	solar zenith angle [=] radians
μ	effective attenuation coefficient [=] m^{-1}
ρ	density of pond solution [=] kg/m^3
τ	dimensionless time

1. INTRODUCTION

1.1 Definition

The salt-gradient solar pond is a body of water that is used as both collector and storage of solar energy. Salt is added to the pond such that the concentration of salt increases with depth, thus inhibiting free convection. The pond can be from 2 to 10 meters deep, with fresh water at the surface and a nearly saturated solution at the bottom. The bottom of such a pond is usually black, for high absorption. When the water in the bottom region of the salt-gradient pond is heated, it tends to remain hotter than the rest of the pond, as convection is suppressed. Thus, heat extraction is made from the bottom of the pond.

1.2 Previous investigation

The first serious research effort in the area of artificially created solar ponds was begun in 1958 by H. Tabor (Ref. 1). This work continued until 1966 when the interest in solar energy decreased due to the low cost of fuel-oil. After the energy crisis of 1973, interest in solar ponds awakened. The Scientific Research Foundation in Israel began solar pond research in 1974. Two demonstration power plants have been set up in Israel, both of which operate at temperatures near 90°C. Similar research was begun in 1974 at Ohio State University in the U.S. Most of the experimental work reported from both Israel and the U.S. has been performed on full-scale ponds, with surface areas ranging from 150 m² to 7000 m².

Some laboratory experiments have been reported, however, which investigate the concentration and temperature gradients, using tanks of 0.5 m diameter (Ref. 2). These tanks were heated from the bottom and thus did not simulate solar radiation.

Wilkins and Pinder have reported work done on a small-scale solar pond model (Ref. 3). The pond they used had surface dimensions of 65 cm $\times$ 65 cm and was 25 cm deep. Their model used partitions to separate the non-convecting layer from the convecting layers, and was exposed to actual radiation in Vancouver.

In 1981, investigators at VKI attempted to model the "saturated" solar pond, with radiation supplied by five halogen lamps (Ref. 4).

The present study differs from the others in that a non-convecting solar pond, without partitions, was modelled on a small scale with controlled artificial sunlight. The experimental results are then compared to the results from a numerical model.

1.3 The motivation for laboratory modelling

If solar ponds are to be used for energy production, a model is needed to test various designs and improvements. A typical solar pond has a surface area on the order of 1000 m². Thus it would be highly impractical to build a full-size solar pond to test any new idea or possible improvement. There are many existing computer simulations of solar ponds (Refs. 5,6,7,8).

Numerical models are limited, however, to the inclusion of phenomena that can be described mathematically. Although it may be argued that this is always possible, it is certainly not always practical. Thus the need for reliable small-scale laboratory models becomes evident.

2. THEORY

2.1 Basic principle

Solar radiation is received by the pond through the pond surface. Some of the incoming radiation is reflected by the surface and some is absorbed near the surface (see Fig. 1). Much of the radiation reaches the bottom of a shallow (< 10 m) pond and is absorbed by the absorbing bottom. Figure 2 shows the amount of transmitted radiation as a function pond depth. It can be seen from this figure that 40% of the incoming radiation can reach the bottom of a 1.5 m pond. Thus, the bottom should absorb the heat and consequently re-radiate it, heating the pond from the bottom. In a pure water pond, the hot water would be lighter than the colder surface water and free convection would begin, mixing the water and allowing the heat to escape into the atmosphere through the surface. In a salt-gradient pond, however, there exist dissolved salts in the pond in proportions that increase with pond depth. That is, the solution at the pond surface contains very little salt and that at the pond bottom is nearly saturated. This increase in solution density counteracts the decrease in density due to the temperature change, thus keeping the hot solution at the bottom of the tank. The stability requirement can be expressed as :

$$\frac{\partial \rho}{\partial h} = \left(\frac{\partial \rho}{\partial T} \right)_q \frac{\partial T}{\partial h} + \left(\frac{\partial \rho}{\partial q} \right)_T \frac{\partial q}{\partial h} > 0 \quad (1)$$

where :

ρ = density of pond solution [=] kg/m³

h = distance below the surface (positive downwards) [=] m

T = temperature [=] °C

q = salt concentration [=] $\frac{\text{kg}}{\text{m}^3}$

As long as the criteria expressed in equation (1) is maintained, the pond will be non-convecting and the heating phenomena will be heat conduction.

2.2 The convective layers

If the entire pond were truly non-convective, the temperature gradient would be as shown in figure 3a. The gradients circled, however, quickly become great enough to overcome the suppressive action of the density gradient and convection begins in the zones shown in figure 3b. Thus in practice, a salt-gradient pond is composed of three layers :

- (1) The upper convective zone (UCZ).
- (2) The non-convective zone (NCZ).
- (3) The lower convective zone (LCZ).

The parallel temperature and density gradients occur in the non-convecting zone, as shown in figure 4.

2.3 The non-dimensional equations (Ref. 5)

A heat balance over a small layer in the non-convecting zone yields the following equation :

$$\frac{\partial T}{\partial t} = \alpha \left(\frac{\partial^2 T}{\partial h^2} \right) + \frac{I_h \mu}{C_p} \sec \theta_r \quad (2)$$

where :

t = time [=] s

α = thermal diffusivity = $\frac{k}{\rho C_p}$ [=] $\frac{m^2}{s}$

μ = effective attenuation coefficient = m^{-1}

C_p = heat capacity of solution [=] $\frac{J}{kg^\circ C}$

$$I_h = \text{radiation at a given pond depth} \\ = I_s (1-F) \exp(-\mu[h-\delta] \sec \theta_r) [=] \frac{W}{m^2}$$

$$\theta_r = \text{refracted angle} = \sin^{-1} \left[\frac{\sin \theta_z}{n} \right] [=] \text{ rad}$$

$$\theta_z = \text{solar zenith angle} [=] \text{ rad}$$

$$n = \text{refractive index of solution} [=] \text{ non-dimensional}$$

$$f = \text{fraction of radiation absorbed in a small distance, } \delta, \\ \text{of solution, non dimensional}$$

$$\delta = \text{small distance in which fraction } F \text{ is absorbed} [=] \text{ m}$$

$$I_s = \text{irradiance just beneath the pond surface} [=] \frac{W}{m^2}$$

In equation (2) it is assumed that heat transfer occurs in one direction only. The depth of a solar pond is ordinarily much, much smaller than either the length or the width, making this assumption good for such an application. Also, it is assumed that all the radiation reaching the bottom is absorbed by the bottom. An equivalent situation occurs when some radiation is reflected from the bottom, in diffuse form, but is consequently absorbed in the storage zone (the lower convecting zone).

The solution of eq.(2) requires one initial condition and two boundary conditions. The initial condition can be chosen. One boundary condition evolves from a heat balance over the upper convecting zone

$$\frac{\partial T_s}{\partial t} = \frac{I_s}{\rho h_1 C_p} \left[1 - (1-F) \exp\{-\mu(h-\delta) \sec \theta_r\} \right] \\ + \frac{k}{\rho h_1 C_p} \left(\frac{\partial T}{\partial h} \right)_{h=h_1} - \frac{Q_{LS}}{\rho h_1 C_p} \quad (3)$$

where :

T_s = temperature in the upper convecting zone [=] °C

h_1 = depth of the upper convecting zone [=] m

Q_{LS} = rate of energy loss at the surface [=] W/s m²

The first term on the right represents the heat absorption in the UCZ due to radiation. The second term represents the heat conduction across the boundary between the NCZ and the UCZ.

The last term represents heat lost through the pond surface.

The boundary condition at the bottom can be found by performing a similar heat balance over the LCZ.

$$\frac{\partial T_b}{\partial t} = \frac{(1-F)}{\rho D_s C_p} I_s \exp[-\mu(D-\delta)\sec\theta_r] - \frac{k}{\rho D_s C_p} \left(\frac{\partial T}{\partial h}\right)_{h=D} \quad (4)$$

$$- \frac{Q_{LG}}{\rho D_s C_p} - \frac{Q_D}{\rho D_s C_p} \quad (4)$$

where :

T_b = temperature in the LCZ [=] °C

D_s = depth of the LCZ [=] m

D = h_1 + depth of the NCZ [=] m

k = thermal conductivity of sol'n [=] W/m°C

Q_{LG} = rate of energy lost to the ground [=] J/m²

Q_D = rate of energy transfer to load [=] J/m²

The first term on the right represents the heat absorption in the LCZ. The second term represents the heat conduction across the boundary between the LCZ and the NCZ. The third term represents the losses to the ground and the last term represents the heat withdrawn from the pond to meet the load.

To non-dimensionalize equations 2, 3 and 4, it is necessary to choose a characteristic time, temperature and distance. The characteristic temperature is chosen as simply T_0 , a reference temperature, which can be the initial pond temperature, or the ground temperature, or in any other convenient way. The characteristic distance is chosen as D , the combined depth of NCZ and UCZ. The characteristic time is chosen as $\frac{D^2}{\alpha}$, which can be thought of as a "thermal travelling time" over the distance D . Thus equations 2, 3 and 4 become, in dimensionless form,

$$\frac{\partial \theta}{\partial \tau} = \frac{\partial^2 \theta}{\partial Z^2} + \frac{D^2 I_h \mu \sec \theta_r}{k T_0} \quad (5)$$

$$\begin{aligned} \frac{\partial \theta_s}{\partial \tau} = & \frac{D^2 I_s}{k T_0 h_1} \left[1 - (1-F) \exp \{-\mu(h_1 - \delta) \sec \theta_r\} \right] \\ & + \frac{D}{h_1} \left(\frac{\partial \theta}{\partial Z} \right)_{Z=Z_1} - \frac{U_{LS} D^2}{k h_1} (\theta_s - \theta_a) \end{aligned} \quad (6)$$

$$\begin{aligned} \frac{\partial \theta_b}{\partial \tau} = & \frac{D^2 (1-F) I_s}{k T_0 D_s} \exp \left[-\mu(D - \delta) \sec \theta_r \right] - \frac{D}{D_s} \left(\frac{\partial \theta}{\partial Z} \right)_{Z=1} \\ & - \frac{U_{LG} D^2}{k D_s} (\theta_b - \theta_{GW}) - \frac{Q_D D^2}{k T_0 D} \end{aligned} \quad (7)$$

where :

$$\theta = \frac{T}{T_0}$$

$$\tau = \frac{\alpha t}{D^2}$$

$$Z = \frac{h}{D}$$

$$\theta_s = \frac{T_s}{T_0}$$

$$\theta_b = \frac{T_b}{T_0}$$

U_{LG} = heat transfer coefficient at pond bottom [=] $W/m^2 \cdot ^\circ C$

U_{LS} = heat transfer coefficient at surface [=] $W/m^2 \cdot ^\circ C$

$$\theta_a = \frac{T_{\text{ambient}}}{T_0}$$

$$\theta_{GW} = \frac{T_{\text{ground}}}{T_0}$$

Several dimensionless "numbers", or parameters, appear in the formulation of the above equations :

(1) The Fourier number = $F_0 = \frac{\alpha \hat{t}}{D^2}$ where t = characteristic time [=] LC ($\hat{t} \neq \frac{D^2}{\alpha}$ here, in order to choose a $\hat{t}$ to maintain the physical meaning of the numbers). F_0 gives the magnitude of the contribution to the change in temperature in the NCZ by conduction.

(2) $N1 = \frac{I_s \hat{t}}{\alpha C_p T_0}$ = the magnitude of the contribution to the change in the NCZ by radiation

(3) $N2 = \frac{I_s \hat{t}}{\rho h_1 C_p T_0}$ = the magnitude of the contribution to the change in temperature in the UCZ due to radiation

(4) $N3 = \frac{k \hat{t}}{\rho h_1 C_p D}$ = the magnitude of the contribution to the change in temperature in the UCZ due to conduction

(5) $N4 = \frac{\hat{t} U_{LS}}{\rho h_1 C_p}$ = the magnitude of the contribution to the change in temperature in the UCZ due to losses through the surface

$$(6) \quad N5 = \frac{I_s \hat{t}}{T_0 \rho D_s C_p} = \text{the magnitude of the contribution to the change in temperature in the LCZ due to radiation}$$

$$(7) \quad N6 = \frac{k \hat{t}}{\rho D_s C_p D} = \text{the magnitude of the contribution to the change in temperature in the LCZ due to conduction}$$

$$(8) \quad N7 = \frac{U_{LG} \hat{t}}{\rho D_s C_p} = \text{the magnitude of the contribution to the change in temperature in the LCZ due to losses to the ground}$$

In this formulation, we will not consider the load term, as this study is concerned with the behavior of a solar pond with no heat load. For a typical solar pond of total depth 1.5 meters, the following values can be calculated for the dimensionless numbers :

$$\left. \begin{array}{l} F_0 \approx 10^{-2} \\ N1 \approx 10^{-2} \end{array} \right\} \text{NCZ}$$

$$\left. \begin{array}{l} N2 \approx 10^2 \\ N3 \approx 10^{-1} \\ N4 \approx 10^{-1} \end{array} \right\} \text{UCZ}$$

$$\left. \begin{array}{l} N5 \approx 1 \\ N6 \approx 10^{-1} \\ N7 \approx 10^{-1} \end{array} \right\} \text{LCZ}$$

Since, in the NCZ, $F_0 \approx N1$, both the magnitude of $N1$ and F_0 must be respected. Since in the UCZ, $N2 \gg N3$ and $N2 \gg N4$, only $N2$ need be modelled. Similarly, in the LCZ, $N5 \gg N6$ and $N5 \gg N7$, so $N6$ and $N7$ can be sacrificed. Thus, four numbers must be respected in any experimental model : F_0 , $N1$, $N2$ and $N5$.

2.4 Discretization of the equations

The non-dimensional equations 5-7 must be discretized for solution on the VAX computer. A Crank-Nicholsen scheme (implicit/explicit) was used. Using a forward time discretization and centered space discretization equation 5 becomes :

$$\begin{aligned} \frac{\theta_i^{n+1} - \theta_i^n}{\Delta \tau} = & \frac{1}{2} \left[\frac{\theta_{i+1}^{n+1} - 2\theta_i^{n+1} + \theta_{i-1}^{n+1}}{\Delta Z^2} \right] \\ & + \frac{1}{2} \left[\frac{\theta_{i+1}^n - 2\theta_i^n + \theta_{i-1}^n}{\Delta Z^2} \right] + \left[\frac{D^2 I_h \mu \sec \theta_r}{k T_0} \right]_i \end{aligned} \quad (8)$$

Using a forward discretization in both time and space, equation 6 becomes :

$$\begin{aligned} \frac{\theta_1^{n+1} - \theta_1^n}{\Delta \tau} = & \frac{1}{2} \frac{D}{h_1} \left[\frac{\theta_2^{n+1} - \theta_1^{n+1}}{\Delta Z} \right] + \frac{1}{2} \frac{D}{h_1} \left[\frac{\theta_2^n - \theta_1^n}{\Delta Z} \right] \\ & + \frac{D^2 I_s}{k T_0 h_1} \left| 1 - (1-F) \exp\{-\mu(h_1 - \delta) \sec \theta_r\} \right| \\ & + \left[\frac{U_{LS} D^2}{k h_1} \theta_a \right] - \frac{1}{2} \frac{U_{LS} D^2}{k h} \theta_1^{n+1} - \frac{1}{2} \frac{U_{LS} D^2}{k h} \theta_1^n \end{aligned} \quad (9)$$

Using a forward time discretization and a backward space discretization, equation 7 becomes :

$$\begin{aligned}
 \frac{\theta_N^{n+1} - \theta_N^n}{\Delta \tau} = & - \frac{1}{2} \frac{D}{D_s} \left(\frac{\theta_N^{n+1} - \theta_{N-1}^{n+1}}{\Delta Z} \right) - \frac{1}{2} \frac{D}{D_s} \left(\frac{\theta_N^n - \theta_{N-1}^n}{\Delta Z} \right) \\
 & + \left[\frac{D^2 (1-F) I_s}{k T_0 D_s} \exp \left(-\mu (D-\delta) \sec \theta_r \right) \right] + \left(\frac{U_{LG} D^2 \theta_{GR}}{k D_s} \right) \\
 & - \frac{1}{2} \frac{U_{LG} D^2}{k D_s} \theta_N^{n+1} - \frac{1}{2} \frac{U_{LG} D^2}{k D_s} \theta_N^n
 \end{aligned} \tag{10}$$

(Note that the heat withdrawal term has been dropped)

Equations 8, 9 and 10 can be programmed in Fortran to set up a tridiagonal matrix to solve for θ in a time-marching style (see Appendix 1 for the program listing). The Crank-Nicholsen scheme is unconditionally stable.

2.5 Temperature behavior

As the pond is heated at a constant heat input one would expect an exponential increase in temperature. When cycling occurs, the average heat input (average with respect to time) is decreased and thus the maximum temperature would be less than that with the same constant heat. Unequal cycling, with the time 'on' greater than the time 'off' would result in an intermediate maximum temperature.

3. EXPERIMENT

3.1 Apparatus

3.1.1 The pond

The model used for these experiments had a square surface area of 0.8281 m^2 . The metal tank was lined on the inside wall with 4 cm of glass bead insulation (see Appendix 2). A pond depth of 30 cm was used with a mylar sheet floating on the surface. The purpose of the surface sheet was to prevent excessive losses due to evaporation. A photograph of the pond appears in figure 5.

3.1.2 The sun

Four halogen lamps were used to supply artificial sunlight to the pond. They were situated at a height that provided energy to the pond somewhat uniformly and of magnitude (at pond surface) of 550 W/m^2 . Figure 6 shows the radiation isolines at the pond surface. The standard deviation of the data was 45.7 W/m^2 , which is 8.2% of the average. For the cycling phase the "sun" was controlled by a microprocessor clock.

3.1.3 Temperature measurements

The temperature of the pond was measured by twelve Copper-Constantan thermocouples at the positions shown in Table 1. The temperature measurement chain is shown schematically in figure 7. A mechanical scanning device, the "clop-clop", was implemented to scan the thermocouples every 14 minutes. An electronic T-reference was used that also provided amplification for the signal to be received by the data logger. The data logger recorded the amplified signal on magnetic tape to be later processed by the PDP computer.

3.1.4 Salt concentration measurements

A probe, operating on optical principles, was developed to measure the concentration of MgCl_2 in the pond. A schematic of the measurement chain is shown in figure 8. A laser beam is directed into a 1 mm plastic optical fiber by a focusing device (see Fig. 9 for detail). The optical fiber then makes a U-turn. This U-turn is exposed to the solution in which the concentration is to be measured. As the laser beam hits the fiber wall, some of the light is refracted into the solution and some is reflected back into the fiber. The amount of light that is refracted into the solution is a function of the index of refraction of the solution which, in turn, is a function of salt concentration. Thus, a measure of the light intensity change through the bend is a measure of the salt concentration. To measure the intensity of light leaving the solution, a photo-resistor is used in the receiving network as shown in figure 10, and the output is read in volts. Seven probe shapes were tested (Fig. 11). The final shape chosen was probe number 7, whose calibration curve is shown in figure 12.

3.2 The procedure

3.2.1 Filling

The pond was filled using a port at the bottom of the tank. It was filled in layers, adding 40 μ fresh water first.

Then 40 μ of 0.05 $\frac{\text{gMgCl}_2}{\text{ml soln}}$ solution was added, very slowly, so as not to mix the two layers. The concentrations were increased, as shown in figure 13, until the last layer of 0.3 $\frac{\text{gMgCl}_2}{\text{ml soln}}$ was added. The last layer was 12 cm deep to induce an effective LCZ. During filling, a concentration scan was performed to monitor the filling method.

3.2.2 Heating

The lights were turned on and the pond was heated for 75 hours. Data was taken intermittently during this period. Concentration scans were performed during the test and at its completion.

3.2.3 Cooling

After 75 hours of heating, the lights were shut off and the pond was allowed to cool for 70 hours. During the cooling phase temperature data was taken automatically every 14 minutes. At the end of the test, a concentration scan was made.

3.2.4 Day/night cycling

To study the cycling in the steady-state mode, the pond was first heated for several days until a surface temperature of about 40°C was reached. Then the controlling clock was set for 4.8 hours on, 4.8 hours off. A run of 16 hours was taken. Then the clock was set for 4.8 hours on, 2.93 hours off, and 60 hours of data were recorded. During all cycling phases, temperature data was taken automatically every 14 minutes on magnetic tape. At the completion of the cycling tests, a concentration scan was made.

3.3 Uncertainty analysis

3.3.1 Temperature measurements

3.3.1.1 Estimation of uncertainty

The temperatures were computed using the following formula :

$$T = - \frac{\sqrt{B^2 - 4AC}}{2A}$$

where :

$$B = 8.03 \pm 0.01$$

$$A = 0.00641 \pm 0.00001$$

$$C = - \text{DIG} \pm 10$$

(where DIG = the numerical value recorded on tape).

Thus, the uncertainty can be estimated using the following formula :

$$\delta T = \left[\left(\frac{\partial T}{\partial B} \delta B \right)^2 + \left(\frac{\partial T}{\partial A} \delta A \right)^2 + \left(\frac{\partial T}{\partial C} \delta C \right)^2 + \left(\frac{\partial T}{\partial \text{DIG}} \delta \text{DIG} \right)^2 \right]^{1/2}$$

For $T = 60^\circ$, DIG = 500 and

$$\delta T = 2^\circ$$

Thus, the uncertainty is $\sim 6\%$.

3.3.1.2 Radiation effects

The most important thermocouple error would most likely be from radiation. Figure 14 compares two sets of data taken at the same time. One was taken with the lights off and the other with the lights on to observe the radiation effects on the thermocouple measurements. It can be clearly seen that the effects of radiation are felt only at the first thermocouple near the surface. From these data it was decided not to include a correction for radiation effects.

3.3.2 Concentration measurements

The final probe tested has a repeatability of ± 0.015 volts. The calibration procedure has a great influence on the uncertainty. A linear formula is used for the temperature variation with volts.

$$C = mV + b$$

If the standard solutions are accurate to $\pm 5\%$, one can assume that m and b are accurate to about 5% also.

$$m = - 0.212 \pm 0.010$$

$$b = 0.239 \pm 0.012$$

The uncertainty in C can then be calculated using :

$$\delta C = \left[\left(\frac{\partial C}{\partial m} \delta m \right)^2 + \left(\frac{\partial C}{\partial b} \delta b \right)^2 + \left(\frac{\partial C}{\partial V} \delta V \right)^2 \right]^{1/2}$$

Using this formula for

$$C = 0.22$$

$$V = 4.16$$

one obtains :

$$\delta C = 0.05 \text{ g/ml}$$

or

$$\frac{0.05}{0.22} = 22\%$$

4. THE NUMERICAL MODEL

Equations 8, 9 and 10 (presented in section 2.4) were programmed, in FORTRAN, to be run on the VAX computer. First the equations were solved with no radiation in the program DECAY (see Appendix I). Then, in the program HEAT (Appendix I), the radiation effects were added. Then, the two programs were combined in SWITCH (Appendix I), to enable the day/night cycling to be simulated.

Runs were made that compared with the experimental heating, cooling and cycling. For the experimental comparison, the following parameters were used :

$$h_1 = 0.4 \text{ cm}$$

$$D = 18 \text{ cm}$$

$$D_s = 12 \text{ cm}$$

$$\mu = 0.1 \text{ m}^{-1}$$

$$I_s = 550 \text{ W/m}^2$$

$$\Delta\tau = 0.00397$$

$$\Delta Z = 0.1$$

$$u_{LS} = 0$$

$$u_{LG} = \begin{cases} 1.125 \text{ W/m}^2\text{°C} & \text{lights "off"} \\ 0 & \text{lights "on"} \end{cases}$$

5. ANALYSIS OF RESULTS*

5.1 Experimental

5.1.1 Heating

5.1.1.1 Data

The series of profiles shown in figure 15 are selected from the data taken during the heating phase. Curve 1 represents the initial conditions of the pond, that is, nearly uniform temperature. The uppermost data point of each curve is 30 cm (pond surface) and the next point is at 27 cm (see Table 1). Thus, one can say from data presented here, that the UCZ is less than 3 cm thick. That is,

$$0 < h_1 < 3 \text{ cm}$$

The data shows nearly uniform temperatures for the bottom 12 cm. Thus,

$$D_s \cong 12 \text{ cm}$$

A pronounced temperature gradient is formed during the first 8 hours of heating, representing exaggerated heat absorption in the first zone. In the subsequent curves, the gradient becomes less pronounced, as the heat is convected through to the lower regions.

Figures 16a,b,c represent graphs of the data taken during heating that express the temperature as a function of time of three of the 12 thermocouple positions. Each curve represents an exponential increase with time. One can see the time constant is smaller near the pond surface and larger near the

* The complete set of raw data is stored on floppy disk and is available on request.

pond bottom. In the series of figures the effect of radiation coming in at the window can be clearly seen. There are three "humps" in the data that can be observed at $t \approx 6$ hours, $t \approx 30$ hours and $t \approx 55$ hours. These times correspond to late afternoon from 15 to 17h on each of the three testing days.

Figure 17 is the same time history for the average temperature during heating. The three "humps" are clearly visible here also.

5.1.1.2 Heat storage during the heating phase

An analysis of the pond heat storage during the heating phase can be made from the data shown in figure 17. The heat input was calculated by the known radiation at the pond surface. The energy stored in the pond was calculated by

$$\text{heat stored} = mC_p \Delta T(t)$$

where :

m = mass of pond = 293 kg

C_p = heat capacity of pond = 3634 J/kg°C

$\Delta T(x)$ = temperature difference from $t = 0$ to t .

In such a manner, figure 18 was generated. The minimum storage appears to be about 30%.

5.1.1.3 Global heat loss coefficient

A global heat balance on the pond yields :

$$mC_p \frac{dT}{dt} = I_s S - HS(T - T_a) \quad (11)$$

S = pond surface area = [m]

where :

H = global heat loss coefficient [=] W/m²°C

Using equation (11), one can solve for $H(T-T_a)$. The variation of $H\Delta T$ is shown in figure 19. As expected, $H\Delta T$ increases with time, that is, as the average temperature increases.

5.1.2 Cooling

Temperature profiles taken during the cooling phase are shown in figure 20. Curve 1 is the initial condition, the heated tank. In the first 9 hours, a drastic change takes place as the temperature gradient changes sense. Heat is lost quickly at the pond surface. After 54 hours of cooling (curve 7), there is still heat storage in the LCZ.

The time variations of the temperature at the twelve positions in the tank are shown in figures 21a-1. The outside radiation effects in the afternoon can again be clearly seen. The greatest effect of this is at the surface, smoothing out in the pond middle, and being felt again, but to a lesser degree, at the pond bottom. This indicates that absorption occurs at the top and at the bottom, the greater amount being absorbed at the top. As in the heating phase, the time constant is smallest at the pond surface. Figure 22 shows the average temperature variation with time during the cooling phase.

5.1.3 Cycling

5.1.3.1 Equal intervals

Figures 23a-c show the temperature variation with time of three of the twelve thermocouple positions during the cycling experiment. Figure 23a at the pond surface, shows a cyclic wave with a 10 hour period and large amplitude. This represents the strong effects of the radiation at the surface. As one moves further into the pond the cyclic variation decays until it is no longer seen at all. At the bottom of the NCZ the temperature is nearly constant with time, revealing the very stable nature of the pond at this point. Near the pond bottom,

a 10 hour cycle is again observed, but with a magnitude less than that at the top. This indicates that the absorption at the bottom is less than that at the top.

5.1.3.2 Unequal intervals

Figures 24a-1 show the results of cycling tests run in the form of 5 hours on and 3 hours off. The same type of behaviour as described in section 5.1.3.1 appears in these figures.

The experiments were run by heating the tank, then performing the 5 on/5 off cycling beginning with the hot tank. Then the 5 on/3 off cycling was begun immediately after. Thus, one would expect to see the temperatures decrease as the maximum overall temperature decreases (see § 2.5), then decrease again as the average heat input is again decreased. The series of data taken did exhibit this behaviour, but the temperature changes were very small and occurred over long periods of time. Thus, it is not possible to illustrate this behaviour with the data shown here.

5.2 Numerical

5.2.1 Heating

Figures 25a-c show comparisons of the numerical results with the experimental data for three times in the heating phase; 5 hours, 24 hours and 48 hours. Although the shape of the curves agree in all cases, the actual temperature difference between experimental and numerical increases with time. The differences are due to the simplifications in the numerical model in describing the absorption of light in the pond. Also, it is expected that the experimental model would reach higher temperatures than predicted, as the additional radiation received through the window was not included in the numerical study.

5.2.2 Cooling

Figs. 26a,b,c show similar results for the cooling phase. The same comments apply to these as those made in section 5.2.1. There is, as shown in figure 28, a difference in slope at the pond bottom. From this one can conclude that the bottom losses are not correctly modelled.

5.2.3 Cycling

The results from the cycling experiments appear graphically in Figs. 27a,b. Note that the greatest difference between the two models occurs at the pond surface. This supports the conclusion that the difference results from :

- (1) Pond properties not modelled - especially the plastic cover.
- (2) Radiation input from the windows.
- (3) Simplified absorption model.

5.3 Concentration measurements

Figure 28a is a concentration profile taken during the filling of the pond. One can see the distinct layers, that is, the evidence that, during filling, the layers did not become mixed.

Figure 28b shows the concentration profile during the tests, verifying the stability of the pond.

Figure 28c shows the concentration profile after completion of all the tests. A gradient is still present, verifying the stability of the pond, but there is clear evidence of the upward diffusion of salt. There was initially 68.4 kg of salt added to the pond. Taking the area under the curve of figure 28c to compute the amount of salt yields 63.7 kg salt remaining in the pond. This represents a 7% salt loss.

Some salt was definitely lost from the solution by deposits on the tank bottom, and also through small leaks in the pond near the thermocouples. But the concentration measurements are highly uncertain and thus no quantitative analysis can be made concerning the salt loss.

6. CONCLUSIONS

Both the experimental model and the numerical model exhibited behavior characteristic of solar ponds. That is, the stable region is at the bottom of the NCZ with absorption in the upper and lower convecting zones. There is heat storage at the bottom evidenced in both.

The numerical model was found to be very sensitive to the depths of the three zones, which are chosen a priori. It is also very sensitive to the model used for absorption in the various layers. That is, to effectively use the model, one must know how radiation will be absorbed in the pond being modelled.

The experimental model acted in quite a "one-dimensional" way, as supported by the agreement between the numerical model and the experimental data. To ensure the same absorption characteristics as in a full-size pond, one need only respect the agreement of water quality and construction materials, if actual sunlight is used.

The problem becomes more difficult, however, when artificial light is used. The spectrum of the artificial light is not exactly the same as the spectrum of sunlight and thus the absorption characteristics are also different.

Finally, from the modelling attempted in this work, one can conclude that the modelling of solar ponds both experimentally and numerically is not only possible but feasible and should be investigated further.

7. RECOMMENDATIONS FOR FUTURE WORK

7.1 Numerical model

The numerical model could be improved by better modelling the pond loss (i.e., temperature-dependent heat loss coefficients). The validity of the analysis of the important dimensionless parameters could be checked using the numerical model.

It would be interesting to compare the results of the model with full-scale field tests.

7.2 Experimental

A longer test, with different cycling times, could be run to observe the phenomena described by section 2.5.

The experimental data could be compared with full-scale field tests.

If artificial light is to be used, an in-depth study of the absorption characteristics of the light in comparison with sunlight should be made.

The concentration probe, as described in section 3.1.4 could be further improved to reduce experimental uncertainty and make it easier to use.

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<u>Thermocouple number</u>	<u>Distance from pond bottom (cm)</u>
1	3
2	6
3	9
4	11.5
5	13
6	14.5
7	16
8	18
9	21
10	24
11	27
12	30

TABLE 1

APPENDIX 1 - PROGRAM LISTINGS

- (a) Numerical - cooling
- (b) Numerical - heating
- (c) Numerical - cycling
- (d) Program to solve tridiagonal matrix
- (e) Plot - temperature vs height
- (f) Plot - temperature vs time

(a)

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100 DIMENSION A(50),B(50),C(50),D(50),PHI(50),X(50),TEMP(50)
200 DIMENSION A1(100),B1(100),C1(100),D1(100),F(100)
300 TYPE 11
400 11 FORMAT(1X,'ENTER NUMBER OF SEGMENTS')
500 READ(5,12)N
600 12 FORMAT(13)
700 TYPE 13
800 13 FORMAT(1X,'ENTER NUMBER OF TIME STEPS')
900 READ(5,12)ITMAX
1000 TYPE 14
1100 14 FORMAT(1X,'ENTER DELTA T')
1200 READ(5,15)DELT
1300 15 FORMAT(F10.5)
1400 TYPE 16
1500 16 FORMAT(1X,'ENTER DELTA X')
1600 READ(5,15)DELX
1700 TYPE 30
1800 30 FORMAT(1X,'ENTER FRACTION OF RADIATION REFLECTED FROM BO
1900 TION')
2000 E READ(5,15)FRAC
2100 DO 3000 I=2,N
2200 X(I)=X(I-1)+DELX
2300 3000 CONTINUE
2400 X(1)=0
2500 TYPE 1001
2600 1001 FORMAT(1X,'ENTER REFERENCE TEMPERATURE')
2700 READ(5,15)IZERO
2800 C CALCULATE G AND P
2900 TYPE 22
3000 22 FORMAT(1X,'ENTER DEPTH OF UCZ IN CM')
3100 READ(5,15)XTOP
3200 TYPE 24
3300 24 FORMAT(1X,'ENTER DEPTH OF DCZ IN CM')
3400 READ(5,15)DEPTH
3500 TYPE 23
3600 23 FORMAT(1X,'ENTER DEPTH OF LCZ IN CM')
3700 READ(5,15)XBOT
3800 Q=(DEPTH+XTOP)/XTOP
3900 P=-(DEPTH+XTOP)/XBOT
4000 C CALCULATE INITIAL SOLUTION
4100 TYPE 25
4200 25 FORMAT(1X,'ENTER INITIAL CONDITIONS IN NON-DIM FORM')
4300 DO 700 IK=1,N
4400 READ(5,15)PHI(IK)
4500 700 CONTINUE
4600 DO 2000 I=1,N
4700 TEMP(I)=PHI(I)*TZERO
4800 X(I)=FLOAT(I-1)*DELX
4900 2000 CONTINUE
5000 C PRINT INITIAL SOLUTION
5100 WRITE(50,20)
5200 DO 600 II=1,N
5300 WRITE(50,21)X(II),PHI(II),TEMP(II)
5400 CONTINUE
5500 TMAX=FLOAT(ITMAX)*DELT
5600 C CALCULATE A(I),B(I),C(I)
5700 C TC IS THE THERMAL CONDUCTIVITY OF THE POND IN W/MK
5800 TC=0.596
5900 C HR IS THE TOP LOSS COEFFICIENT IN W/M2K
6000 C HI IS THE RADIATION IN W/M2
6100 HI=0
6200 C UBU IS THE EFFECTIVE EXTINCTION COEFFICIENT IN 1/M
6300 UBU=1
6400 C HIR IS THE REFLECTED RADIATION
6500 HIR=.6*FRAC*HI
6600 HR=TC*100./DEPTH
6700 C PHIAHB IS THE AMBIENT TEMPERATURE
6800 PHIAHB=19./TZERO
6900 C CONE=-HR*(DEPTH+XTOP)**2/(TC*XTOP*100.)
7000 A1(1)=(-Q*DELT)/(2.*DELX)
7100 7200 C UB IS THE BOTTOM LOSS COEFFICIENT IN W/M2K
7200 UB=1.125
7300 C1(0)=-UB*(XTOP+DEPTH)**2/(TC*XBOT*100.)
7400 B1(1)=1.+(Q*DELT)/(2.*DELX)-CONE*DELT/2.
7500 B1(0)=1.-(P*DELT)/(2.*DELX)-C1(0)*DELT/2.
7600 C1(1)=0.
7700 C1(0)=(P*DELT)/(2.*DELX)
7800 A1(0)=0.
7900 DO 100 I=2,N-1
8000 Q=1.
8100 A1(I)=(-Q*DELT)/(2.*DELX**2)
8200 B1(I)=1.+(Q*DELT)/(DELX**2)
8300 C1(I)=A1(I)
8400
8500

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8600 100 CONTINUE
8700 C TIME LOOP:
8750 IIAU=0
8800 DO 200 J=1,ITMAX
8900 T=T+DELT
8950 IIAU=ITAU+1
9000 C CALCULATE EI
9100 C CALCULATE H,F,AND G
9200 H=HR*(DEPTH+XTOP)**2*PHIAMB/(TC*XTOP*100.)+(DEPTH+XTOP)**
9300 A 2*(1.-(.6*EXP(-UMU*(XTOP-6.)/100.)))+HI/(TC*TZERO*XTOP*100.)
9400 G +HIR*(1.-(.6*EXP(-UMU*((DEPTH+XBOT-6.)/100.)))*(DEPTH+XTOP
9500 I )**2/(TC*T
9600 H ZERC+XTOP*100.)
9700 DO 800 IK=1,N
9800 CI(IK)=HI*.6*EXP(-UMU*(FLOAT(IK-1)*(DEPTH+XTOP)-6.)/100.)
9900 M +HIR*.6*EXP(-UMU*((1-FLOAT(IK-1))*(DEPTH+XTOP)+XBOT-6.)/
10000 N 100.)
10100 F(IK)=(DEPTH+XTOP)**2*CI(IK)*UMU/(TC*TZERO*100**2)
10200 C WRITE(70,26)F(IK)
10300 800 CONTINUE
10400 C 26 FORMAT(1X,'F=',F10.5)
10500 PHIG IS THE TEMPERATURE OF THE GROUND
10600 PHIG=15./TZERO
10700 G=UB*(DEPTH+XTOP)**2*PHIG/(TC*XBOT*100.)+(DEPTH+XTOP)**
10800 B 2*.6*HI*EXP(-UMU*(DEPTH+XTOP-6.)/100.)/(TC*TZERO*XBOT*100.)
10900 K +(DEPTH+XTOP)**2*.6*PHIAMB*HIR*EXP(-UMU*(XBOT-6.)/100.)/(
11000 L TC*TZERO*XBOT*100.)
11100 D(1)=(O*DELT*PHI(2))/(2.*DELX)+(1.-(O*DELT)/(2.*DELX)*PHI(
11200 A 1))+(DELT/2.)*(H+G)+CONF*PHI(1)*DELT/2.
11300 C WRITE(70,27)D(1)
11400 27 FORMAT(1X,'D1=',F10.5)
11500 D(N)=(P*DELT)/(2.*DELX)+1.)*PHI(N)-((P*DELT)/(2.*DELX))*P
11600 B HI(N-1)+(DELT/2.)*(G+G)+CTWO*PHI(N)*DELT/2.
11700 C WRITE(70,28)D(N)
11800 28 FORMAT(1X,'DN=',F10.5)
11900 DO 300 I=2,N-1
12000 D(I)=(O*DELT*PHI(I+1))/(2.*DELX**2)+(1.-(O*DELT)/(DELX
12100 D **2))*PHI(I)+(O*DELT)/(2.*(DELX**2))*PHI(I-1)+(DELT/2.
12200 E )*(F(I)+F(I))
12300 C WRITE(70,29)D(1)
12400 29 FORMAT(1X,'D=',F10.5)
12500 300 CONTINUE
12600 C CALCULATE SOLUTION AT TIME T
12700 DO 301 JJ=1,N
12800 A(JJ)=A1(JJ)
12900 B(JJ)=B1(JJ)
13000 C(JJ)=C1(JJ)
13100 301 CONTINUE
13200 CALL TRID(A,B,C,D,N,PHI)
13300 DO 2002 I=1,N
13400 TEMP(I)=PHI(I)*TZERO
13500 2002 CONTINUE
13600 C PRINT NEW SOLUTION
13650 IF(ITAU.NE.4)GO TO 55
13700 WRITE(50,19)I
13800 19 FORMAT(1X,'I=',F10.5)
13900 WRITE(50,20)
14000 20 FORMAT(1X,8X,'X',12X,'SOLUTION',8X,'TEMPERATURE')
14100 DO 500 K=1,N
14200 WRITE(50,21)X(K),PHI(K),TEMP(K)
14250 IIAU=0
14300 500 CONTINUE
14350 55 CONTINUE
14400 200 CONTINUE
14500 21 FORMAT(2X,F10.5,8X,F10.5,8X,F10.5)
14600 STOP
14700 END

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(b)

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100 DIMENSION A(50),B(50),C(50),L(50),PHI(50),X(50),TEMP(50)
200 DIMENSION A1(100),B1(100),C1(100),L1(100),F(100)
300 TYPE 11
400 11 FORMAT(1X,'ENTER NUMBER OF SEGMENTS')
500 READ(5,12)N
600 12 FORMAT(13)
700 TYPE 13
800 13 FORMAT(1X,'ENTER NUMBER OF TIME STEPS')
900 READ(5,12)ITMAX
1000 TYPE 14
1100 14 FORMAT(1X,'ENTER DELTA T')
1200 READ(5,15)DELT
1300 15 FORMAT(F10.5)
1400 TYPE 16
1500 16 FORMAT(1X,'ENTER DELTA X')
1600 READ(5,15)DELT
1700 TYPE 30
1800 30 FORMAT(1X,'ENTER FRACTION OF RADIATION REFLECTED FROM BOT
1900 E TION')
2000 READ(5,15)FRAC
2100 DO 3000 I=2,N
2200 X(I)=X(I-1)+DELT
2300 3000 CONTINUE
2400 X(I)=0
2500 TYPE 1001
2600 1001 FORMAT(1X,'ENTER REFERENCE TEMPERATURE')
2700 READ(5,15)TZERO
2800 C CALCULATE Q AND P
2900 TYPE 22
3000 22 FORMAT(1X,'ENTER DEPTH OF UCZ IN CM')
3100 READ(5,15)XUCP
3200 TYPE 24
3300 24 FORMAT(1X,'ENTER DEPTH OF NCZ IN CM')
3400 READ(5,15)DEPTH
3500 TYPE 23
3600 23 FORMAT(1X,'ENTER DEPTH OF LCZ IN CM')
3700 READ(5,15)XBOT
3800 Q=(DEPTH+XUCP)/XUCP
3900 P=-((DEPTH+XUCP)/XBOT
4000 C CALCULATE INITIAL SOLUTION
4100 TYPE 25
4200 25 FORMAT(1X,'ENTER INITIAL CONDITIONS IN NON-DIM FORM')
4300 DO 700 IK=1,N
4400 READ(5,15)PHI(IK)
4500 700 CONTINUE
4600 DO 2000 I=1,N
4700 TEMP(I)=PHI(I)*TZERO
4800 X(I)=FLOAT(I-1)*DELT
4900 2000 CONTINUE
5000 C PRINT INITIAL SOLUTION
5100 WRITE(50,20)
5200 DO 600 II=1,N
5300 WRITE(50,21)X(II),PHI(II),TEMP(II)
5400 600 CONTINUE
5500 TMAX=FLOAT(ITMAX)*DELT
5600 C CALCULATE A(I),B(I),C(I)
5700 C IC IS THE THERMAL CONDUCTIVITY OF THE POND IN W/MK
5800 IC=0.6
5900 C HR IS THE TOP LOSS COEFFICIENT IN W/M2K
6000 C HI IS THE RADIATION IN W/M2
6100 TYPE 31
6200 31 FORMAT(1X,'ENTER INCIDENT RADIATION')
6300 READ(5,15)HI
6400 C UMU IS THE EFFECTIVE EXTINCTION COEFFICIENT IN 1/M
6500 UMU=.1
6600 C HIR IS THE REFLECTED RADIATION
6700 HIR=.6*FRAC*HI
6800 HR=0.
6900 C PHIA*H IS THE AMBIENT TEMPERATURE
7000 PHIA*H=35./TZERO
7100 C ONE=-HR*(DEPTH+XTOP)**2/(TC*XTOP*100.)
7200 A1(I)=(-O*DELT)/(2.*DELT)
7300 C UB IS THE BOTTOM LOSS COEFFICIENT IN W/M2K
7400 UB=0.
7500 C TWO=-UB*(XTOP+DEPTH)**2/(TC*XBOT*100.)
7600 B1(I)=1.+(O*DELT)/(2.*DELT)-CONE*DELT/2.
7700 B1(I)=1.-(P*DELT)/(2.*DELT)-CTWO*DELT/2.
7800 C1(I)=0.
7900 C1(I)=(P*DELT)/(2.*DELT)
8000 A1(I)=0.
8100 DO 100 I=2,N-1
8200 O=1.
8300 A1(I)=(-O*DELT)/(2.*DELT**2)

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      33
8400      B1(I)=1.+(C*DELT)/(DELT**2)
8500      C1(I)=A1(I)
8600      100  CONTINUE
8700      C  TIME LOOP:
8750      ITAU=0
8800      DO 200 J=1,ITMAX
8900      T=I+DELT
8950      ITAU=ITAU+1
9000      C  CALCULATE EI
9100      C  CALCULATE H,F,AND G
9200      H=HR*(DEPTH+XTOP)**2*PHIAB/((C*XTOP*100.)+(DEPTH+XTOP)**
9300      A  2*HI/(C*TZERO*XTOP*100.))
9400      G  +HIR*(EXP(-UMU*((DEPTH+XBOT)/100.))*((DEPTH+XTOP
9500      C  I  )**2/(C*I
9600      C  H  ZERO*XTOP*100.))
9650      C  H=0.
9700      DO 800 IK=1,N
9800      DI(IK)=HI*EXP(-UMU*(FLCAT(IK-1)*(DEPTH+XTOP)/100.))-
9900      M  +HIR*EXP(-UMU*((1-FLCAT(IK-1))*(DEPTH+XTOP)+XBOT)/
10000      N  100.))
10100      F(IK)=(DEPTH+XTOP)**2*DI(IK)*UMU*DELT/(C*TZERO*100**2)
10200      C  WRITE(70,26)F(IK)
10300      800  CONTINUE
10400      26  FORMAT(1X,'F=',F10.5)
10500      C  PHIG IS THE TEMPERATURE OF THE GROUND
10600      PHIG=20./TZERO
10700      G=UB*(DEPTH+XTOP)**2*PHIG/(C*XBOT*100.)
10800      Z  +(DEPTH+XTOP)**2*HI*(DEPTH+XTOP)*(1.-EXP(-UMU*(DEPTH+XTOP)/100
10850      Y  ))/(C+TZERO*XBOT*100.)
10900
11100      D(1)=(G*DELT*PHI(2))/(2.*DELT)+(1.-(G*DELT)/(2.*DELT)*PHI(
11200      A  1))+(DELT/2.)*(H+H)+CCNE*PHI(1)*DELT/2.
11300      C  WRITE(70,27)D(1)
11400      27  FORMAT(1X,'D1=',F10.5)
11500      D(N)=(P*DELT)/(2.*DELT)+1.)*PHI(N)-((P*DELT)/(2.*DELT))*P
11600      B  HI(N-1)+(DELT/2.)*(G+G)+CTBO*PHI(N)*DELT/2.
11700      C  WRITE(70,28)D(N)
11800      28  FORMAT(1X,'DN=',F10.5)
11900      DO 300 I=2,N-1
12000      C(I)=(G*DELT*PHI(I+1))/(2.*DELT**2)+(1.-(G*DELT)/(DELT
12100      D  **2))*PHI(I)+((G*DELT)/(2.*DELT**2))*PHI(I-1)+(DELT/2.
12200      E  )*(F(I)+F(I))
12300      C  WRITE(70,29)D(I)
12400      29  FORMAT(1X,'D=',F10.5)
12500      300  CONTINUE
12600      C  CALCULATE SOLUTION AT TIME T
12700      DO 301 JJ=1,N
12800      A(JJ)=A1(JJ)
12900      B(JJ)=B1(JJ)
13000      C(JJ)=C1(JJ)
13100      301  CONTINUE
13200      CALL TRID(A,B,C,E,N,PHI)
13300      DO 2002 I=1,N
13400      TEMP(I)=PHI(I)*TZERO
13500      2002  CONTINUE
13550      IF (ITAU.NE.4)GO TO 55
13600      C  PRINT NEW SOLUTION
13700      WRITE(50,19)I
13800      19  FORMAT(1X,'I=',F10.5)
13900      WRITE(50,20)
14000      20  FORMAT(1X,8X,'X',12X,'SOLUTION',8X,'TEMPERATURE')
14100      DO 500 K=1,N
14200      WRITE(50,21)X(K),PHI(K),TEMP(K)
14300      500  CONTINUE
14350      ITAU=0.
14375      CONTINUE
14400      200  CONTINUE
14500      21  FORMAT(2X,F10.5,8X,F10.5,8X,F10.5)
14600      STOP
14700      END

```

(c)

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SWITCH.FCR;15

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100      DIMENSION A(50),B(50),C(50),D(50),PHI(50),X(50),TEMP(50)
200      DIMENSION A1(100),B1(100),C1(100),L1(100),F(100)
300      TYPE 11
400      11      FORMAT(1X,'ENTER NUMBER OF SEGMENTS')
500      READ(5,12)N
600      12      FORMAT(13)
700      TYPE 13
800      13      FORMAT(1X,'ENTER NUMBER OF TIME STEPS')
900      READ(5,12)ITMAX
1000     TYPE 14
1100     14      FORMAT(1X,'ENTER DELTA T')
1200     READ(5,15)DELT
1300     15      FORMAT(F10.5)
1400     TYPE 16
1500     16      FORMAT(1X,'ENTER DELTA X')
1600     READ(5,15)DELT
1700     TYPE 30
1800     30      FORMAT(1X,'ENTER FRACTION OF RADIATION REFLECTED FROM BC
1900     E      TION')
2000     READ(5,15)FRAC
2100     TYPE 32
2200     32      FORMAT(1X,'ENTER TIME OF SUNLIGHT IN HOURS')
2300     READ(5,15)ON
2400     TYPE 33
2500     33      FORMAT(1X,'ENTER TIME OF DARK IN HOURS')
2600     READ(5,15)OFF
2700     TYPE 99
2800     99      FORMAT(1X,'ENTER AMBIENT TEMP DURING SUN')
2850     READ(5,15)TSUN
2875     TYPE 98
2887     98      FORMAT(1X,'ENTER AMBIENT TEMP DURING DARK')
2893     READ(5,15)TDARK
2900     DO 3000 I=2,N
3000     X(I)=X(I-1)+DELT
3100     3000    CONTINUE
3200     X(1)=0
3300     TYPE 1001
3400     1001     FORMAT(1X,'ENTER REFERENCE TEMPERATURE')
3500     READ(5,15)TZERO
3600     C      CALCULATE G AND F
3700     TYPE 22
3800     22      FORMAT(1X,'ENTER DEPTH OF UCZ IN CM')
3900     READ(5,15)XIUP
4000     TYPE 24
4100     24      FORMAT(1X,'ENTER DEPTH OF NCZ IN CM')
4200     READ(5,15)DEPTH
4300     TYPE 23
4400     23      FORMAT(1X,'ENTER DEPTH OF LCZ IN CM')
4500     READ(5,15)XBOT
4600     O=(DEPTH+XIUP)/XTCP
4700     P=-(DEPTH+XTOP)/XBOT
4725     ILIGHT=.0858*ON*60./(DEPTH+XTCP)**2
4750     IDARK=.0858*OFF*60./(DEPTH+XTOP)**2-DELT
4800     C      CALCULATE INITIAL SOLUTION
4900     TYPE 25
5000     25      FORMAT(1X,'ENTER INITIAL CONDITIONS IN NON-DIM FORM')
5100     DO 700 IK=1,N
5200     READ(5,15)PHI(IK)
5300     700    CONTINUE
5400     DO 2000 I=1,N
5500     TEMP(I)=PHI(I)*TZERO
5600     X(I)=FLOAT(I-1)*DELT
5700     2000    CONTINUE
5800     C      PRINT INITIAL SOLUTION
5900     WRITE(50,20)
6000     DO 600 II=1,N
6100     WRITE(50,21)X(II),PHI(II),TEMP(II)
6200     600    CONTINUE
6300     IMAX=FLOAT(ITMAX)*DELT
6400     C      CALCULATE A(I),B(I),C(I)
6500     C      TC IS THE THERMAL CONDUCTIVITY OF THE POND IN W/MK
6600     TC=.596
6700     C      HR IS THE TOP LOSS COEFFICIENT IN W/M2K
6800     C      HI IS THE RADIATION IN W/M2
6900     TYPE 31
7000     31      FORMAT(1X,'ENTER INCIDENT RADIATION')
7100     READ(5,15)HIMP
7125     HI=HIMP
7150     TAMP=TSUN
7200     C      UMD IS THE EFFECTIVE EXTINCTION COEFFICIENT IN 1/M
7300     UMD=.1
7400     C      HIR IS THE REFLECTED RADIATION
7500     HR=0.

```

```

7800      COEF=-HR*(DEPTH+XTOP)**2/(TC*XTOP*100.)
7900      A1(1)=(-Q*DELT)/(2.*DELX)
8000      C      UB IS THE BOTTOM LOSS COEFFICIENT IN W/M2K
8100      UB=0.
8500      C1(1)=0.
8600      C1(N)=(P*DELT)/(2.*DELX)
8700      A1(N)=0.
8800      DO 100 I=2,N-1
8900      U=1.
9000      A1(I)=(-Q*DELT)/(2.*DELX**2)
9100      B1(1)=1.+(Q*DELT)/(DELX**2)
9125      CTWO=-UB*(XTOP+DEPTH)**2/(TC*XBOT*100.)
9150      B1(I)=1.+(Q*DELT)/(2.*DELX)-COEF*DELT/2.
9175      B1(N)=1.-(P*DELT)/(2.*DELX)-CTWO*DELT/2.
9200      C1(I)=A1(I)
9300      100    CONTINUE
9400      TIME=0.
9500      T=0.
9600      C      TIME LOOP:
9650      ITAU=0
9700      DO 200 J=1,ITMAX
9800      T=T+DELT
9850      ITAU=ITAU+1
9900      TIME=TIME+DELT
10000     IF (TIME.LT.TLIGHT)GO TO 101
10100     IF (TIME.GE.(TLIGHT+TDARK))TIME=0.
10225     UB=1.125
10237     HI=0.
10243     IF (TIME.EQ.0.)HI=HINF
10250     TAMB=TDARK
10251     C      PHIAMB IS THE AMBIENT TEMPERATURE
10252     PHIAMB=TAMB/TZERO
10300     C      CALCULATE CI
10400     C      CALCULATE H, F, AND G
10500     HIF=.6*FRAC*HI
10600     101    H=HR*(DEPTH+XTOP)**2*PHIAMB/(TC*XTOP*100.)+(DEPTH+XTOP)**
10700     A      2*HI/(TC*TZERO*XTOP*100.)
10800     G      +HIF*(1.-.6*EXP(-UMU*((DEPTH+XBOT-6.)/100.)))*(DEPTH+XTOP
10900     I      )**2/(TC*T
11000     H      ZERO*XTOP*100.)
11100     DO 800 IK=1,N
11200     U1(IK)=HI*EXP(-UMU*(FLCAT(IK-1)*(DEPTH+XTOP))/100.)
11300     M      +HIF*.6*EXP(-UMU*((1-FLCAT(IK-1))*(DEPTH+XTOP)+XBOT-6.)/
11400     N      100.)
11500     F(IK)=(DEPTH+XTOP)**2*CI(IK)*UMU*DELX/(TC*TZERO*100**2)
11600     C      WRITE(70,26)F(IK)
11700     800    CONTINUE
11800     26    FORMAT(1X,'F=',F10.5)
11900     C      PHIG IS THE TEMPERATURE OF THE GROUND
12000     PHIG=15./TZERO
12100     G=UB*(DEPTH+XTOP)**2*PHIG/(TC*XBOT*100.)+(DEPTH+XTOP)**
12200     H      2*HI*(1.-EXP(-UMU*(DEPTH+XTOP)/100.))/(TC*TZERO*XBOT*100.)
12300     K      +(DEPTH+XTOP)**2*.6*PHIAMB*HIF*EXP(-UMU*(XBOT-6.)/100.)/(
12400     L      TC*TZERO*XBOT*100.)
12500     D(1)=(Q*DELT*PHI(2))/(2.*DELX)+(1.-(Q*DELT)/(2.*DELX)*PHI(
12600     A      1))+(DELT/2.)*(H+G)+CONF*PHI(1)*DELT/2.
12700     C      WRITE(70,27)D(1)
12800     27    FORMAT(1X,'D1=',F10.5)
12900     D(N)=((P*DELT)/(2.*DELX)+1.)*PHI(N)-((P*DELT)/(2.*DELX))*P.
13000     B      HI(N-1)+(DELT/2.)*(G+G)+CTWO*PHI(N)*DELT/2.
13100     C      WRITE(70,28)D(N)
13200     28    FORMAT(1X,'DN=',F10.5)
13300     DO 300 I=2,N-1
13400     D(I)=(Q*DELT*PHI(I+1))/(2.*DELX**2)+(1.-(Q*DELT)/(DELX
13500     D      **2))*PHI(I)+(Q*DELT)/(2.*(DELX**2))*PHI(I-1)+(DELT/2.
13600     E      )*(F(I)+F(I+1))
13700     C      WRITE(70,29)D(I)
13800     29    FORMAT(1X,'D=',F10.5)
13900     300    CONTINUE
14000     C      CALCULATE SOLUTION AT TIME T
14100     DO 301 JJ=1,N
14200     A(JJ)=A1(JJ)
14300     B(JJ)=B1(JJ)
14400     C(JJ)=C1(JJ)
14500     301    CONTINUE
14600     CALL TRID(A,B,C,D,N,PHI)
14700     DO 2002 I=1,N
14800     TEMP(I)=PHI(I)*TZERO
14900     2002    CONTINUE
14950     C      IF (ITAU.NE.4)GO TO 55
15000     C      PRINT NEW SOLUTION
15100     WRITE(50,19)I
15200     19    FORMAT(1X,'I=',F10.5)
15300     WRITE(50,20)
15400     20    FORMAT(1X,8X,'X',12X,'SOLUTION',8X,'TEMPERATURE')
15500     DO 500 K=1,N
15600     WRITE(50,21)X(K),PHI(K),TEMP(K)
15700     500    CONTINUE

```

15750 ITAU=0 - 36 -
15775 C 55 CONTINUE
15800 200 CONTINUE
15900 21 FORMAL(ZX,F10.5,RX,F10.5,RX,F10.5)
16000 STOP
16100 END

(d)

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TRID.FCR;2

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```
100      SUBROUTINE TRID(A,B,C,D,E,PHI)
110      C
120      C
130      C
140      C
150      C
160      C
170      C
180      C
190      C
200      C
210      C
220      C
230      C
240      C
250      C
260      C
270      C
280      C
290      C
300      C
310      C
320      C
330      C
340      C
350      C
360      C
370      C
380      C
390      C
400      C
410      C
420      C
430      C
440      C
450      C
460      C
```

SOLVE FOR THE SOLUTION VECTOR BY DOUBLE SWEEP ALGORITHM
FIRST SWEEP - ELIMINATE LOWER DIAGONAL
DO 1 I=2,N
 A(I)=B(I)-C(I)*A(I-1)/E(I-1)
 D(I)=D(I)-C(I)*D(I-1)/E(I-1)
 C(I)=0.
CONTINUE
SECOND SWEEP - DETERMINE SOLUTION VECTOR
PHI(N)=D(N)/B(N)
DO 2 I=1,N-1
 J=N-I
 PHI(J)=(D(J)-A(J)*PHI(J+1))/B(J)
SOLUTION COMPLETE
RETURN
END

(e)

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```
PROGRAM BROWN
LOGICAL*1 YES
DIMENSION IVEC(1),JVEC(4),T(17),X(17),TH(15)
DATA X /3.,6.,9.,11.5,13.,14.5,16.,18.,21.,24.,27.,30.,
      33.,36.,39.,42.,45./
1
      TYPE 1000
1000  FORMAT(' CALCULATIONS WITH OUTPUT LIST [1] ' /
           ' PLOTTER [2] ' /)
      ACCEPT 1010,IOPT
1010  FORMAT(I5)
      IF(IOPT.EQ.1) CALL ASSIGN (2,'BROWN.OUT')
      IF(IOPT.EQ.1) GO TO 5
      TYPE 1012
1012  FORMAT(' TOTAL NUMBER OF DATA POINTS -> ' $)
      ACCEPT 1010,NPTOT
      NMODE=0
      TYPE 777
777   FORMAT(' DO YOU WANT STARS?(Y/N) ' )
      IF(YES) NMODE=7
5      IDEB=0
      IPLOT=0
      NINH=0
      IF(IOPT.EQ.1) GO TO 6
      TYPE 1011
1011  FORMAT(' NUMBER OF POINTS TO SKIP -> ' $)
      ACCEPT 1010,NSKIP
      IF(NSKIP.EQ.0) NSKIP=1
      NCURVE=NPTOT/NSKIP
      NPLOT=0
6      II=1
10      DO 25 I=II,4
          CALL GETVAL (0,IVEC,ISTAT)
          IF(ISTAT.LT.0) GO TO 999
          IF(IDEB.NE.0) GO TO 21
          TYPE 15
15      FORMAT(' T-REFERENCE -> ' $)
          IDEB=1
          ACCEPT 20,TREF
20      FORMAT(F10.0)
21      JVEC(I)=IVEC(1)
25      CONTINUE
C
      IF(IOPT.EQ.1) TYPE 9000,JVEC
9000  FORMAT(1X,4I10)
C
C      AVE=(JVEC(1)+JVEC(2)+JVEC(3)+JVEC(4))/4
C
      DO 30 I=1,17
          CALL GETVAL (0,IVEC,ISTAT)
          T(I)=TREF+
1      (-2.03+SQRT(64.48+0.02564*(FLOAT(IVEC(1)))))/0.01282
30      CONTINUE
C
      IPLOT=IPLOT+1
      IF(IOPT.EQ.2) GO TO 2000
      IF(NINH.NE.0) GO TO 2001
      NINH=1
      XMIN=T(1)
      XMAX=XMIN
2001  DO 2002 I=1,17
          IF(I.EQ.14.OR.I.EQ.16) GO TO 2002
          XMIN=AMIN1(XMIN,T(I))
```

```

      XMAX=AMAX1(XMAX,TC1)
2002  CONTINUE
      WRITE (2,35) T
35    FORMAT(1X,10F8.1)
      WRITE (2,40)
40    FORMAT(1H )
      C
2000  CONTINUE
      IF(IOPT.EQ.1) GO TO 3000
      IF(NSKIP.EQ.1) GO TO 2003
      IF(NODDIPLOT,NSKIP).NE.1) GO TO 3000
2003  IT=0
      DO 2010 I=1,17
      IF(I.EQ.14.OR.I.EQ.18) GO TO 2010
      IT=IT+1
      TNC(IT)=TC(I)
2010  CONTINUE
      CALL LILI (15,TN,X,1,MODE,NCURVE,3,1,1)
      C
      IPLOT=0
      NPLOT=NPLOT+1
      C
3000  DO 50 I=1,27
      CALL GETVAL (0,IVEC,ISTAT)
      IF(IOPT.EQ.1) GO TO 3001
      IF(NPLOT.EQ.NCURVE) GO TO 52
3001  IF(ISTAT.LT.0) GO TO 999
50    CONTINUE
51    CALL GETVAL (0,IVEC,ISTAT)
      IF(ISTAT.LT.0) GO TO 999
      IF(ABS(IVEC(1)).GT.1000) GO TO 51
      IVEC(1)=IVEC(1)
      II=2
      GO TO 10
      C
52    IF(ISTAT.LT.0) GO TO 999
      CALL GETVAL (0,IVEC,ISTAT)
      GO TO 52
999   IDEB=0
      TYPE 55
55    FORMAT(' NEXT RUN [Y/N] : (* )')
      IF(YES()) GO TO 5
      IF(IOPT.NE.1) GO TO 9999
      WRITE(2,35) XMIN,XMAX
      CLOSE (UNIT=2,DISP='PRINT')
9999  STOP
      END

```


(f)

```

PROGRAM BROWN2
LOGICAL*1 YES
DIMENSION IVEC(1),JVEC(4),T(17),X(1000),TNC(1000)

TYPE 1012
FORMAT(' TOTAL NUMBER OF DATA POINTS -> ',*)
ACCEPT 202 NPTOT
1008 ICB=1
IT=0
NOUN=1
DO 7 I=1,1000
X(I)=23333*FLOAT(I-1)
II=1
10 DO 25 I=II,4
CALL GETVAL (0,IVEC,ISTAT)
IF(ISTAT LT.0) GO TO 999
IF(1008 NE.0) GO TO 21
TYPE 15
15 FORMAT(' T-REFERENCE -> ',*)
ICB=1
ACCEPT 20 TREF
20 FORMAT(' T0 = ')
TYPE 101
201 FORMAT(' PROBE NUMBER ,ENTER 100 FOR AVERAGE,-> ',*)
ACCEPT 202 NPROBE
202 FORMAT(' ')
21 IVEC(1)=IVEC(1)
25 CONTINUE

AVE=(IVEC(1)+JVEC(2)+JVEC(3)+JVEC(4))/4

DO 30 I=1,17
CALL GETVAL (0,IVEC,ISTAT)
T(I)=TREF+
1 (-8.03+SQRT(64.48+0.02564*(FLOAT(IVEC(1)))))/0.01282
30 CONTINUE

IT=IT+1
IF(NPROBE.EQ.100)GO TO 500
TNC(IT)=T(NPROBE)
GO TO 3000
500 SUM=0
DO 70 J=1,17
SUM=SUM+T(J)
70 CONTINUE
SUM = SUM-T(14)-T(16)
TNC(IT)=SUM/15

3000 DO 50 I=1,27
CALL GETVAL (0,IVEC,ISTAT)
3001 IF(ISTAT LT.0) GO TO 999
50 CONTINUE
51 CALL GETVAL (0,IVEC,ISTAT)
IF(ISTAT LT.0) GO TO 999
IF(1008(IVEC(1)).GT.1000) GO TO 51
JVEC(1)=IVEC(1)
II=2
GO TO 10

52 IF(ISTAT LT.0) GO TO 999
CALL GETVAL (0,IVEC,ISTAT)
GO TO 32
999 ICB=1

```

```
CALL LILI (NPTOT,K,TN,1,0,NCURVE,3,1,1)
TYPE SS
55  FORMAT(' NEXT RUN (Y/N) : ')
    IF (YES) GO TO 5
9999 STOP
    END
```

APPENDIX 2 - APPARATUS INFORMATION

Insulation



FOAMGLAS®

PROPRIETES PHYSIQUES

Deux types :

1- FOAMGLAS® T2

principalement destiné aux applications pour lesquelles la conductivité thermique représente le facteur prédominant.

COMPOSITION :

Verre cellulaire alumino-silicaté d'une composition spécialement étudiée, totalement inorganique, sans addition de liants

TEMPERATURE D'EMPLOI :

- 260 à + 430°C

POINT DE RAMOLLISSEMENT :

Point de ramollissement du verre : environ 730°C

2- FOAMGLAS® S3,

appliqué plus particulièrement lorsque les exigences en matière de résistance à la compression sont sévères.

ABSORPTION D'EAU : (à l'immersion)

Nulle à l'exception de la rétention momentanée de surface

HYGROSCOPICITE :

Nulle

PERMEABILITE A LA VAPEUR D'EAU :

Nulle, selon norme AFNOR-NFX 41.001 (Essai du C.S.T.B. - Paris)

Deux isolants FOAMGLAS® pourront donc être spécifiés pour les applications dans les domaines du bâtiment, de l'industrie et du froid.

FACTEUR DE RESISTANCE A LA DIFFUSION DE VAPEUR D'EAU :

$\mu : \infty$, Forschungsinstitut für Wärmeschutz, Allemagne (Dr. Cammerer)

CAPILLARITE :

Nulle

RESISTANCE AUX ACIDES :

Résiste à tous les acides communément employés ainsi qu'à leurs vapeurs

INCOMBUSTIBILITE :

Classé M.O.

STABILITE DIMENSIONNELLE :

Parfaite

ISOLEMENT ACOUSTIQUE BRUT AUX FREQUENCES AUDIBLES :

28 dB pour une épaisseur de 10 cm

FOAMGLAS® T2 FOAMGLAS® S3

Dimensions en mm.

Longueur	Largeur
300	450
600	450

Epaisseur
40, 45, 50, 60, 70, 80, 90, 100, 120, 130
50, 60, 70, 80, 90, 100, 120, 130

marquage rouge

M SI

MASSE VOLUMIQUE
(tolérance $\pm 10\%$)

125 kg/m³ 125 kg/m³

**CONDUCTIVITE
THERMIQUE**
(tolérance $\pm 5\%$)

$\lambda - 20^\circ\text{C} : 0,033 \text{ kcal/m.h.}^\circ\text{C}$ $\lambda - 20^\circ\text{C} : 0,038 \text{ W/m K}$
 $0^\circ\text{C} : 0,036 \text{ kcal/m.h.}^\circ\text{C}$ $0^\circ\text{C} : 0,042 \text{ W/m K}$
 $+20^\circ\text{C} : 0,039 \text{ kcal/m.h.}^\circ\text{C}$ $+20^\circ\text{C} : 0,045 \text{ W/m K}$

***RESISTANCE A
LA COMPRESSION**
(valeur moyenne)

5 kg/cm² 490 kPa

**RESISTANCE
A LA FLEXION**

4,5 kg/cm² 440 kPa

**MODULE
D'ELASTICITE
(A LA FLEXION)**

10.000 kg/cm² 980 MPa

**COEFFICIENT
DE DILATATION
LINEAIRE**

$8,5 \times 10^{-6}/^\circ\text{C}$ $8,5 \times 10^{-6}/\text{K}$

**CHALEUR
SPECIFIQUE**

0,20 kcal/kg^{°C} 0,84 kJ/kg K

**DIFFUSIVITE
THERMIQUE A 0°C**

$4,0 \times 10^{-3} \text{ cm}^2/\text{sec.}$ $4,0 \times 10^{-7} \text{ m}^2/\text{sec.}$

Dimensions en mm.

Longueur	Largeur
300	450
600	450

Epaisseur
40, 50, 60, 100
50, 60, 100

marquage bleu

M SI

135 kg/m³ 135 kg/m³

$\lambda - 20^\circ\text{C} : 0,035 \text{ kcal/m.h.}^\circ\text{C}$ $\lambda - 20^\circ\text{C} : 0,041 \text{ W/m K}$
 $0^\circ\text{C} : 0,038 \text{ kcal/m.h.}^\circ\text{C}$ $0^\circ\text{C} : 0,044 \text{ W/m K}$
 $+20^\circ\text{C} : 0,041 \text{ kcal/m.h.}^\circ\text{C}$ $+20^\circ\text{C} : 0,048 \text{ W/m K}$

7 kg/cm² 680 kPa

5,3 kg/cm² 520 kPa

12.000 kg/cm² 1.180 MPa

$8,5 \times 10^{-6}/^\circ\text{C}$ $8,5 \times 10^{-6}/\text{K}$

0,20 kcal/kg^{°C} 0,84 kJ/kg K

$4,0 \times 10^{-3} \text{ cm}^2/\text{sec.}$ $4,0 \times 10^{-7} \text{ m}^2/\text{sec.}$

*Le coefficient de sécurité sera choisi par le bureau d'études en fonction de l'application. Une valeur de 3 est fréquemment adoptée. Sauf indications contraires, les propriétés du verre cellulaire FOAMGLAS® sont données à la température ambiante

FABRIQUÉ PAR



PITTSBURGH CORNING EUROPE S.A.
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 Télex 22277 Picto B.

et correspondent aux méthodes d'essais ASTM N° C 303, C 240, C 165, C 177, C 203, C 355 et E 136. Pour l'isolation des fonds de réservoirs, on se référera à la spécification i 22 - édition 1978.

© FOAMGLAS et PC sont des marques déposées aux Etats Unis et dans d'autres pays.

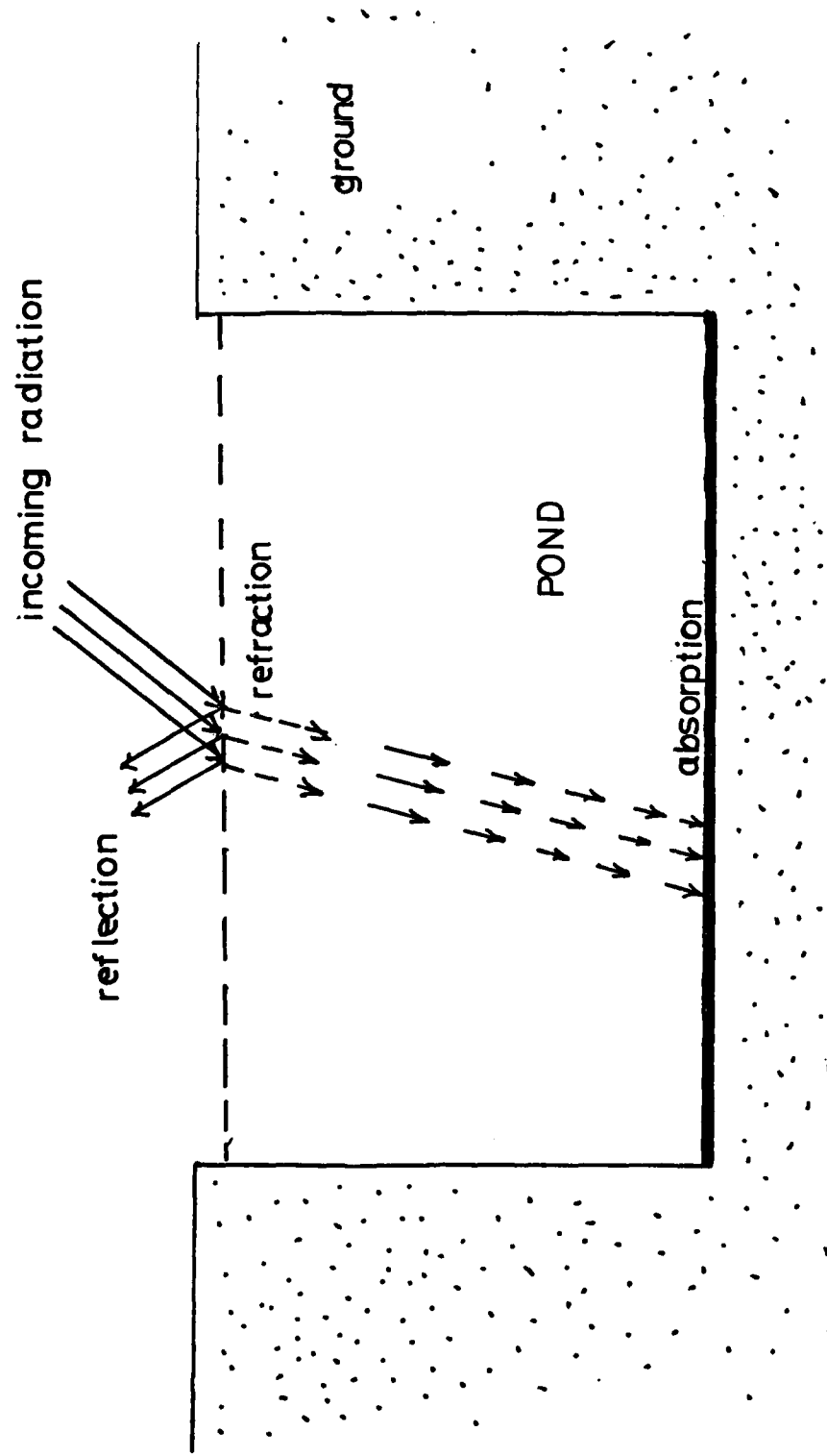


FIGURE 1
RADIATION PHENOMENA IN A SOLAR POND

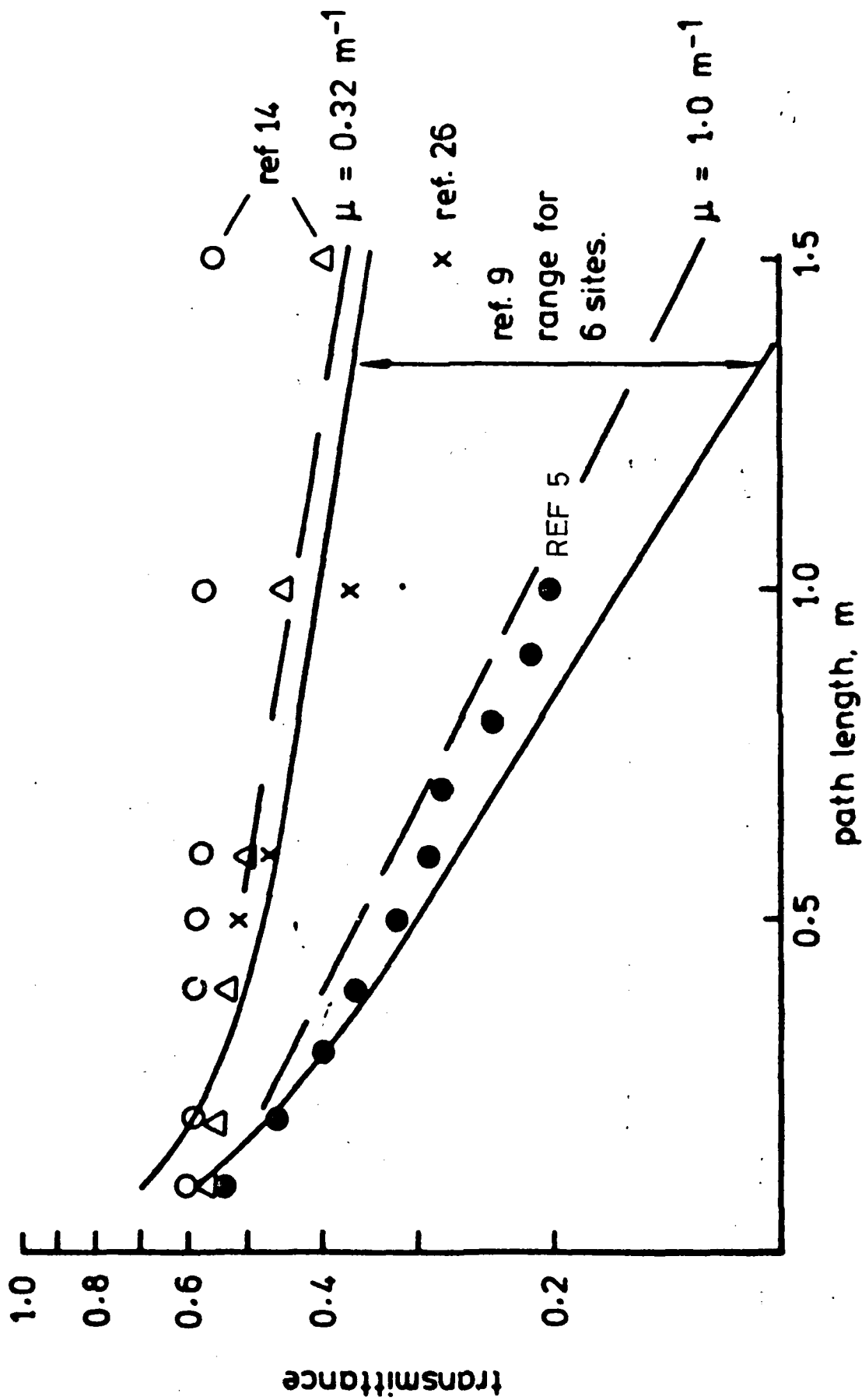


FIGURE 2
LIGHT ABSORPTION IN WATER

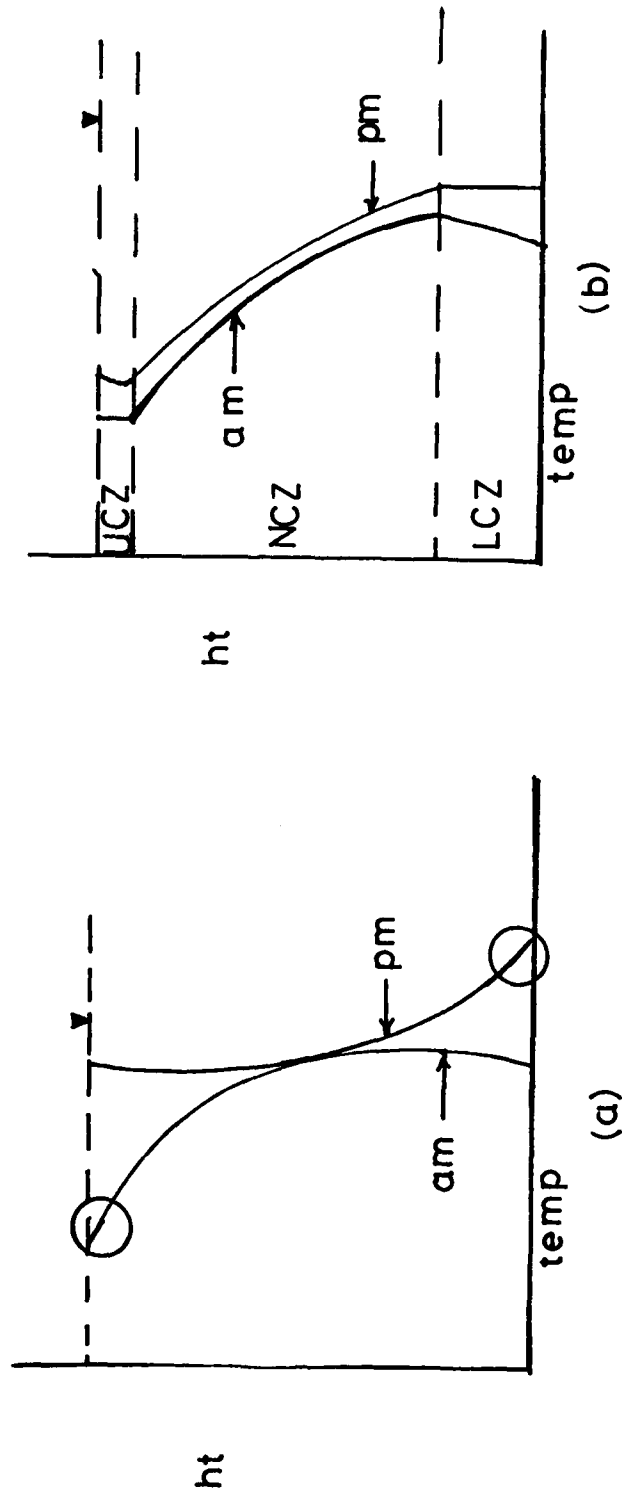
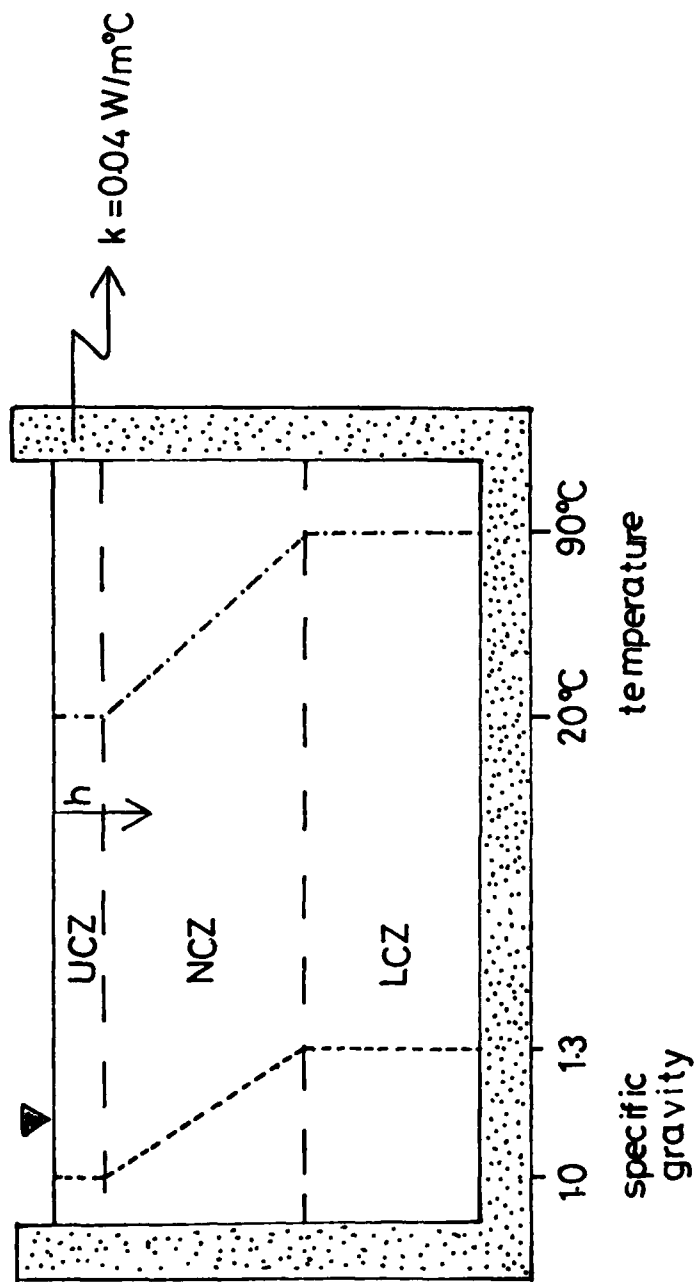


FIGURE 3
THE CONVECTIVE ZONES



$$\frac{\partial \rho}{\partial h} = \left(\frac{\partial \rho}{\partial T} \right)_q \frac{\partial T}{\partial h} + \left(\frac{\partial \rho}{\partial q} \right)_T \frac{\partial q}{\partial h} > 0$$

THE GRADIENTS

FIGURE 4

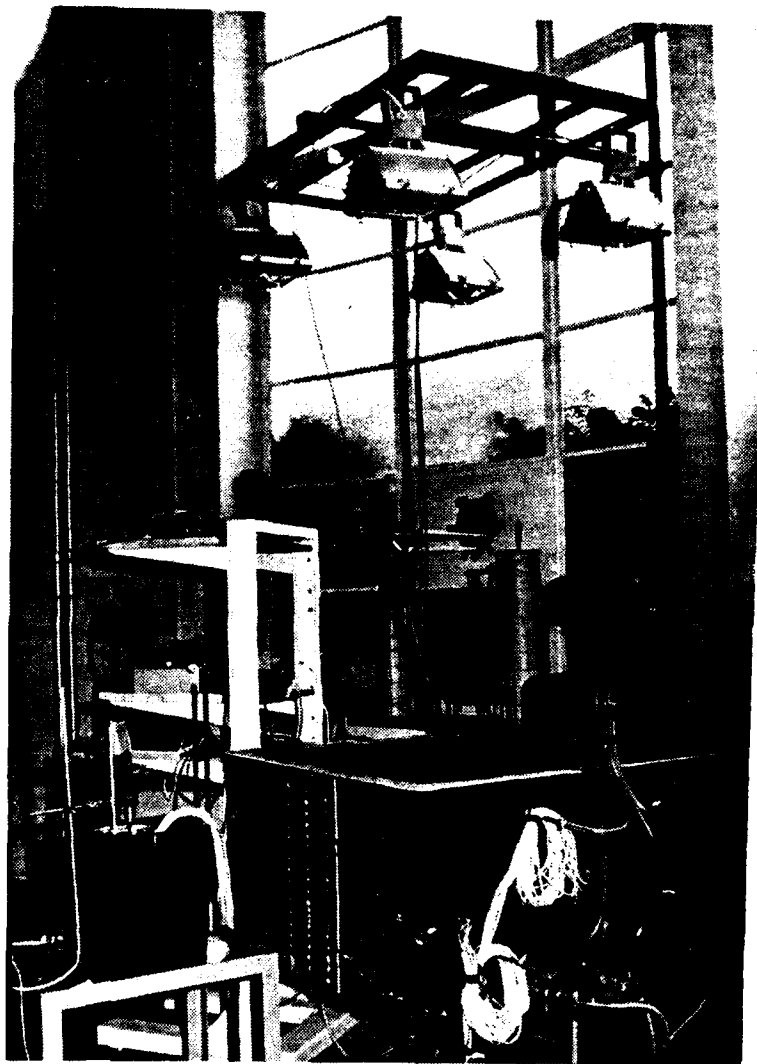


FIGURE 5 - POND STRUCTURE

Watts/m²

◇	4.5664E+02
△	4.7645E+02
□	4.9627E+02
▽	5.1609E+02
×	5.3591E+02
○	5.5573E+02
*	5.7555E+02
#	5.9536E+02
×	6.1518E+02

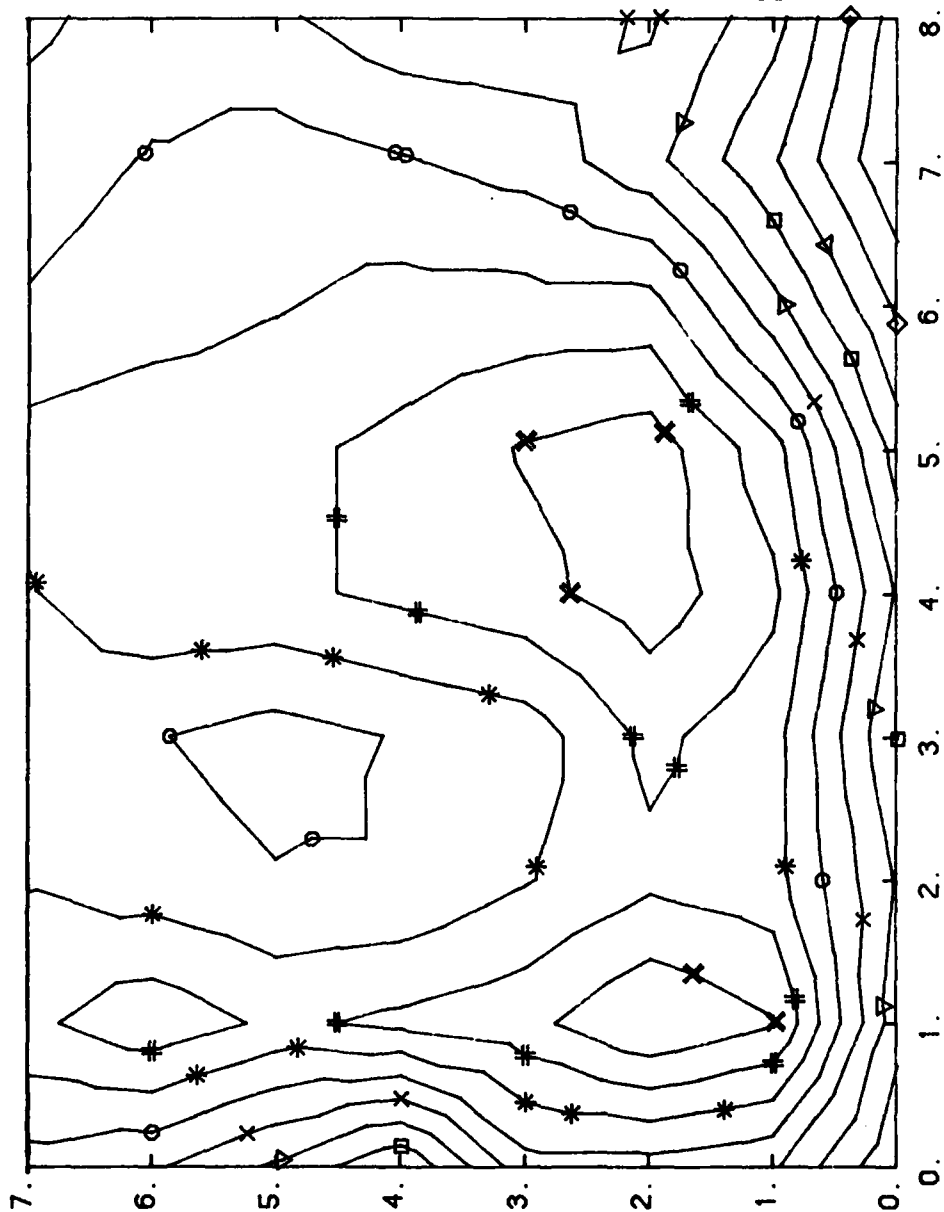
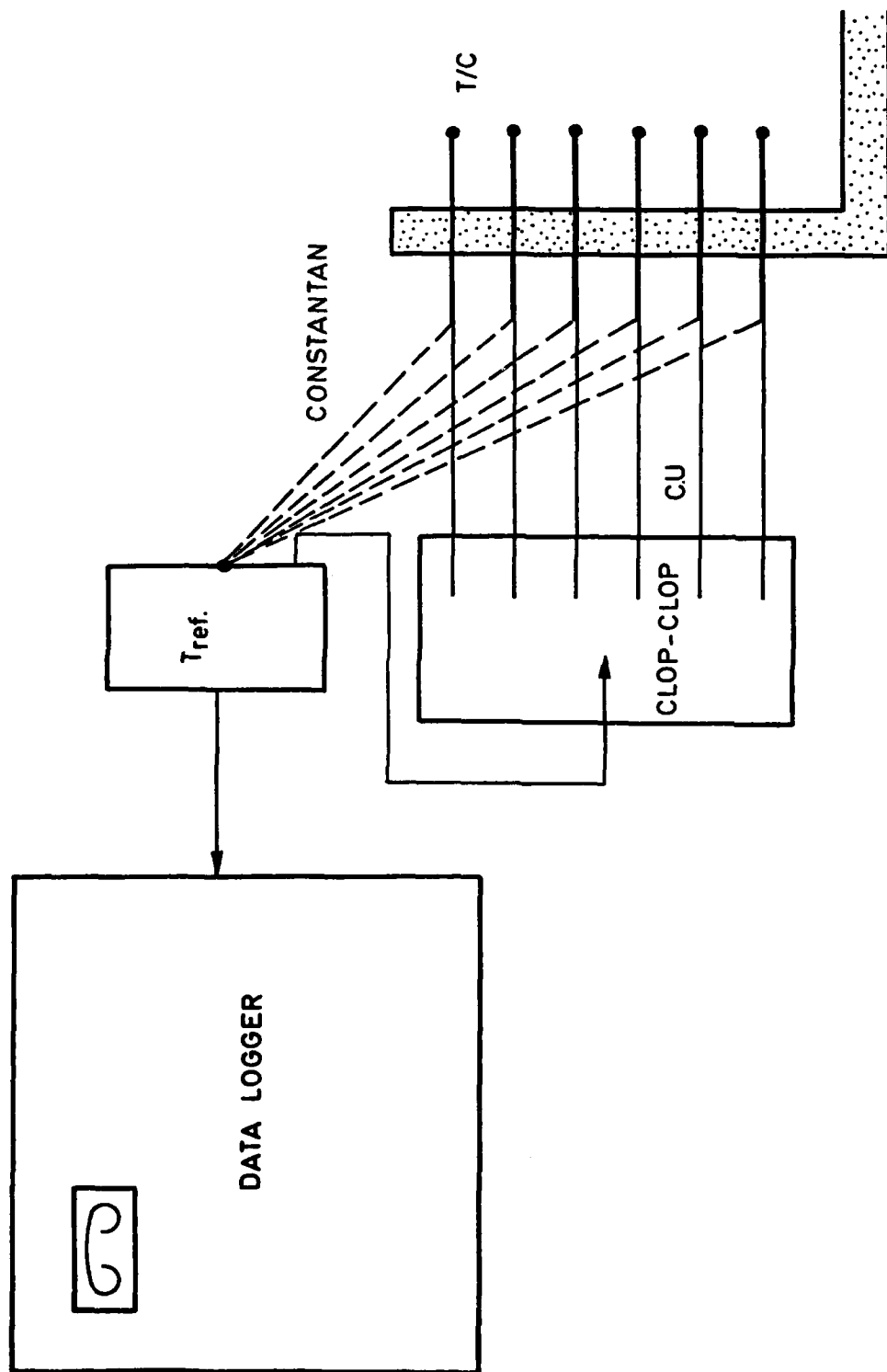
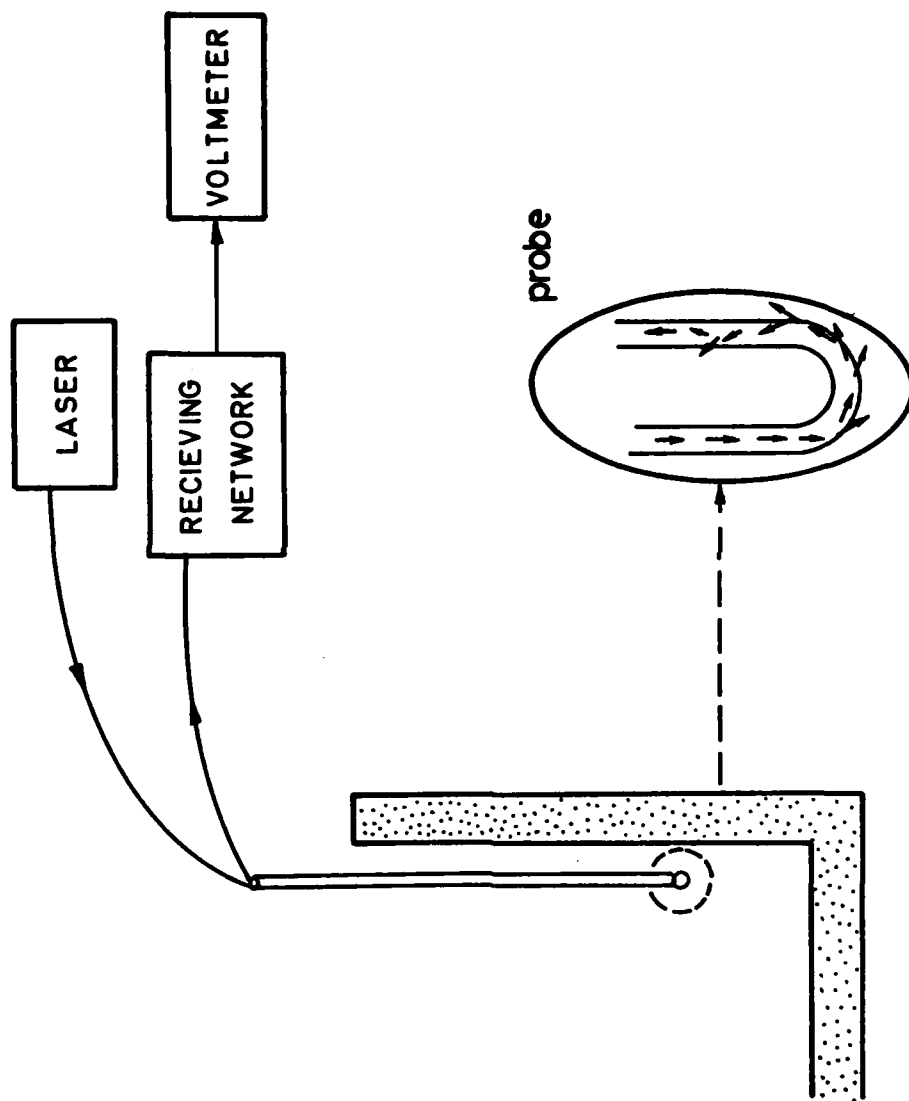


FIGURE 6 : RADIATION FIELD ISOLINES



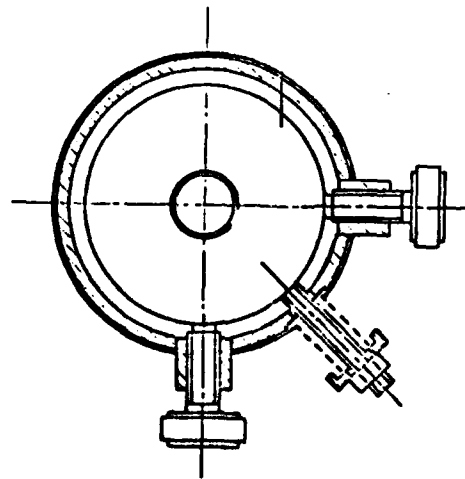
TEMPERATURE MEASUREMENT CHAIN
FIGURE 7



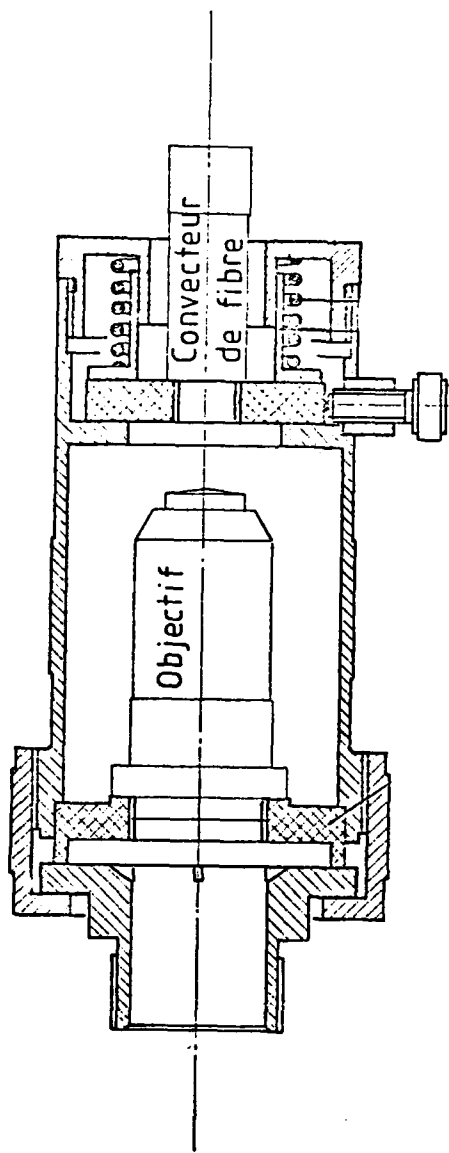
CONCENTRATION MEASUREMENT CHAIN

FIGURE 8

section a



a]



THE FOCUSING DEVICE

FIGURE 9

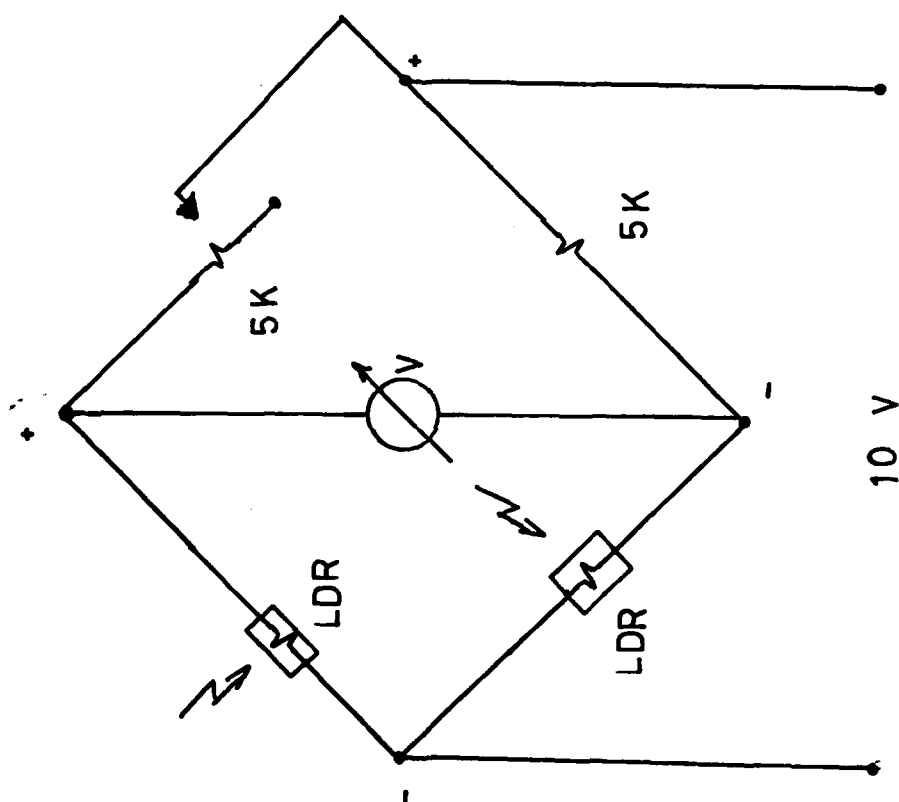


FIGURE 10
RECEIVING NETWORK

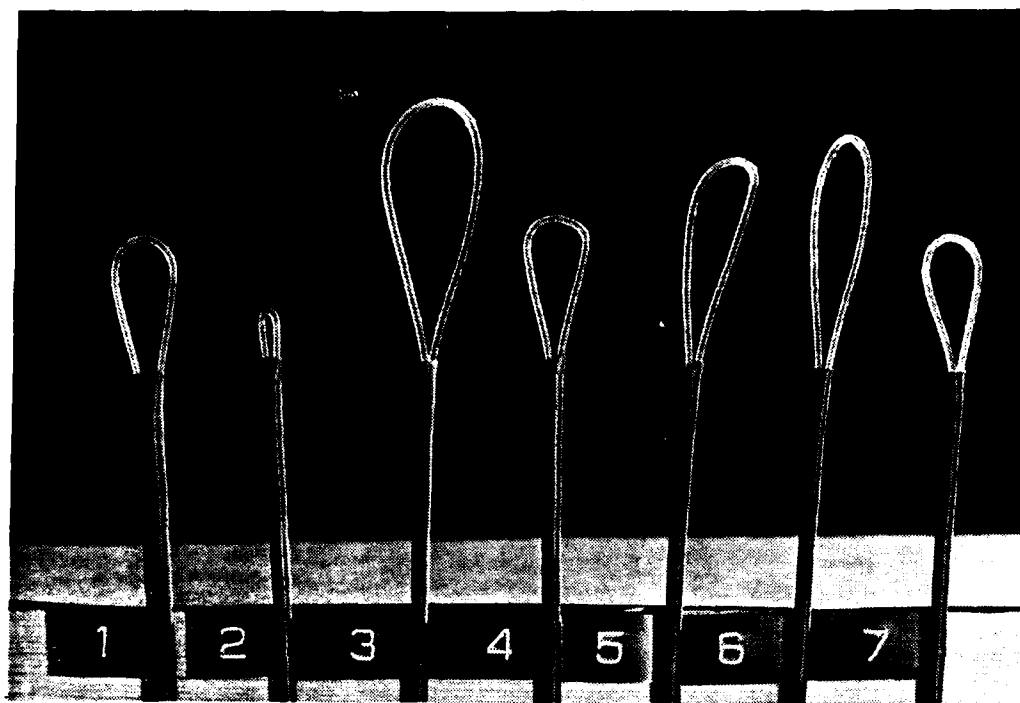
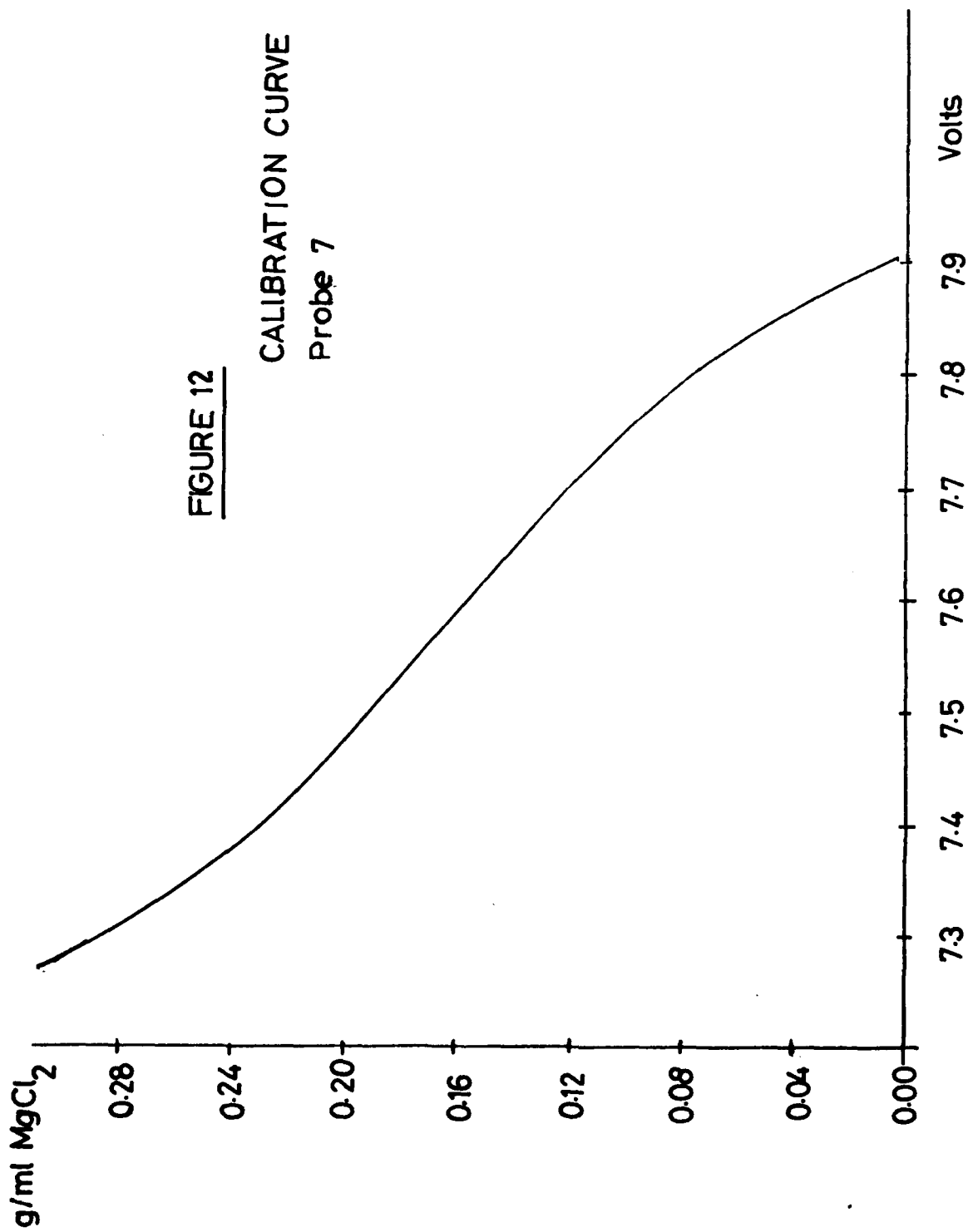


FIGURE 11 - PROBE TIPS



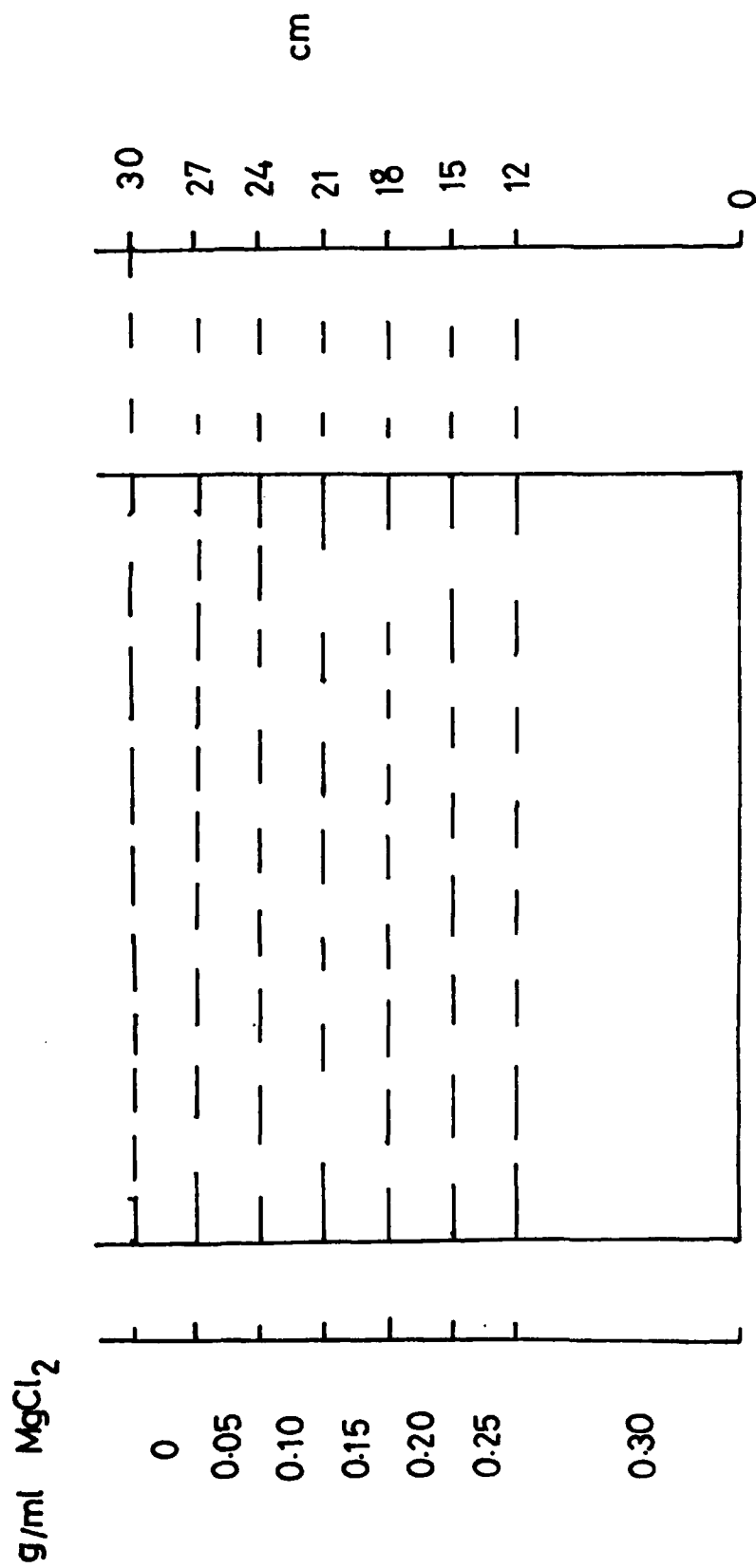


FIGURE 13
POND FILLING

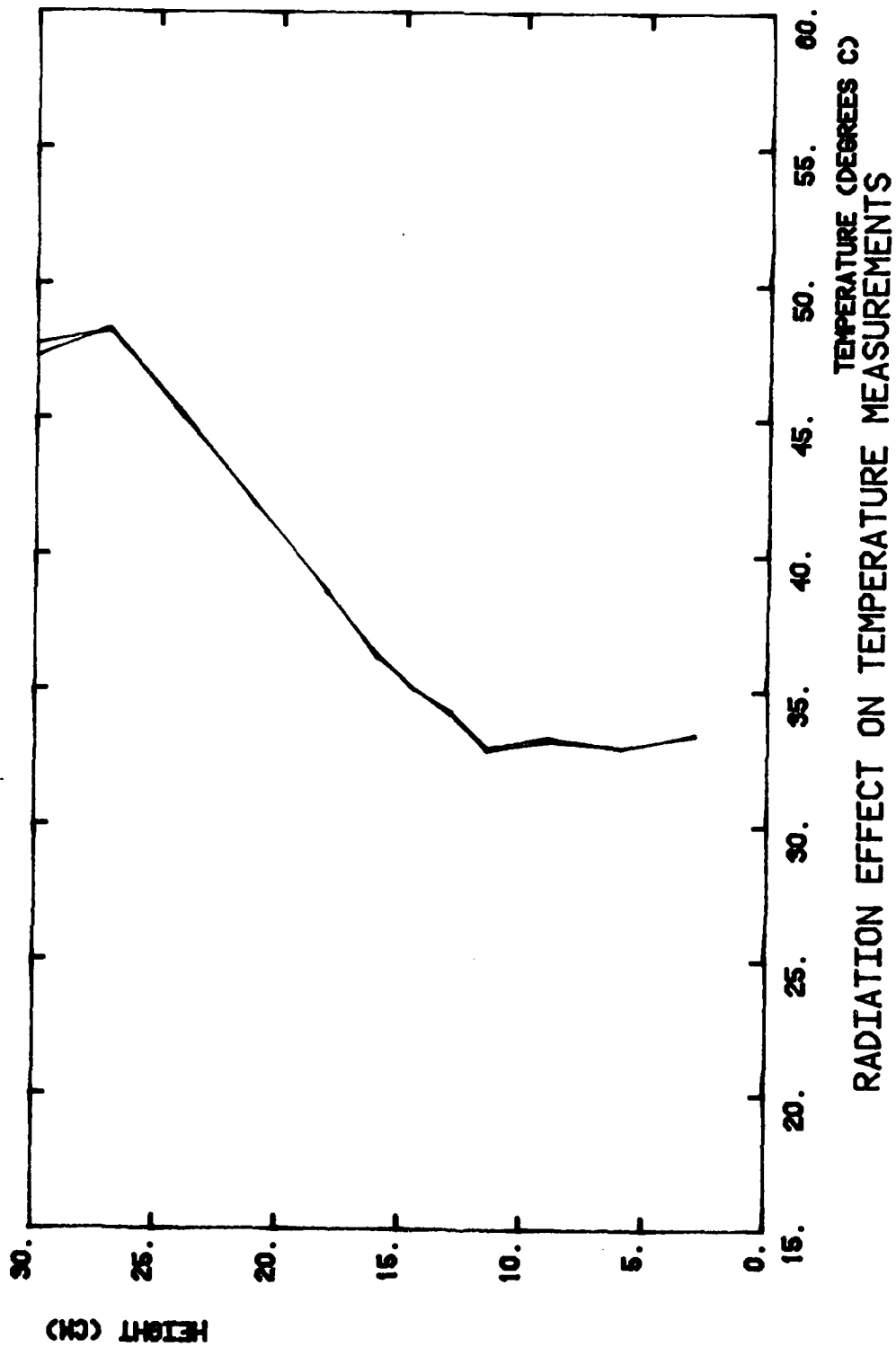
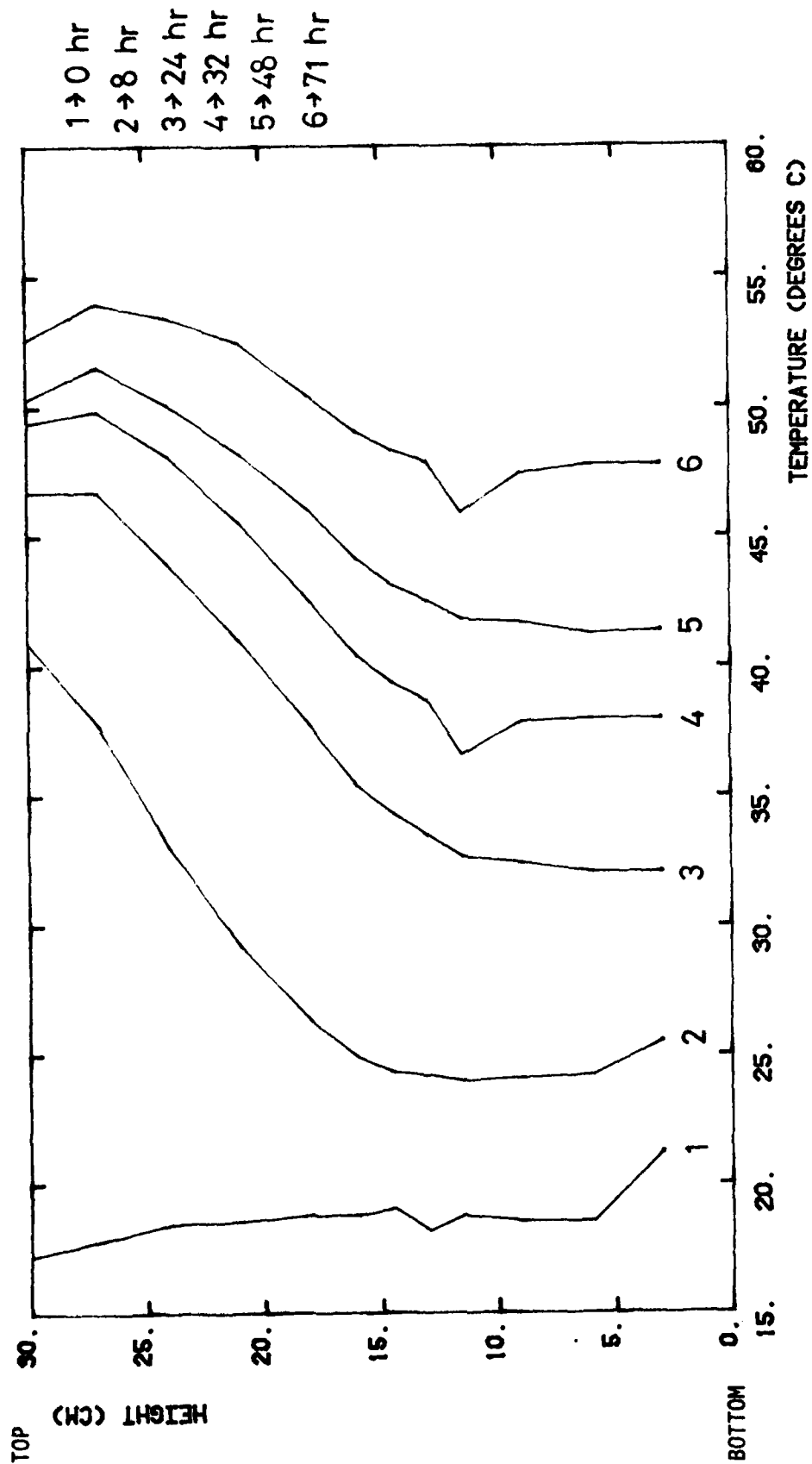
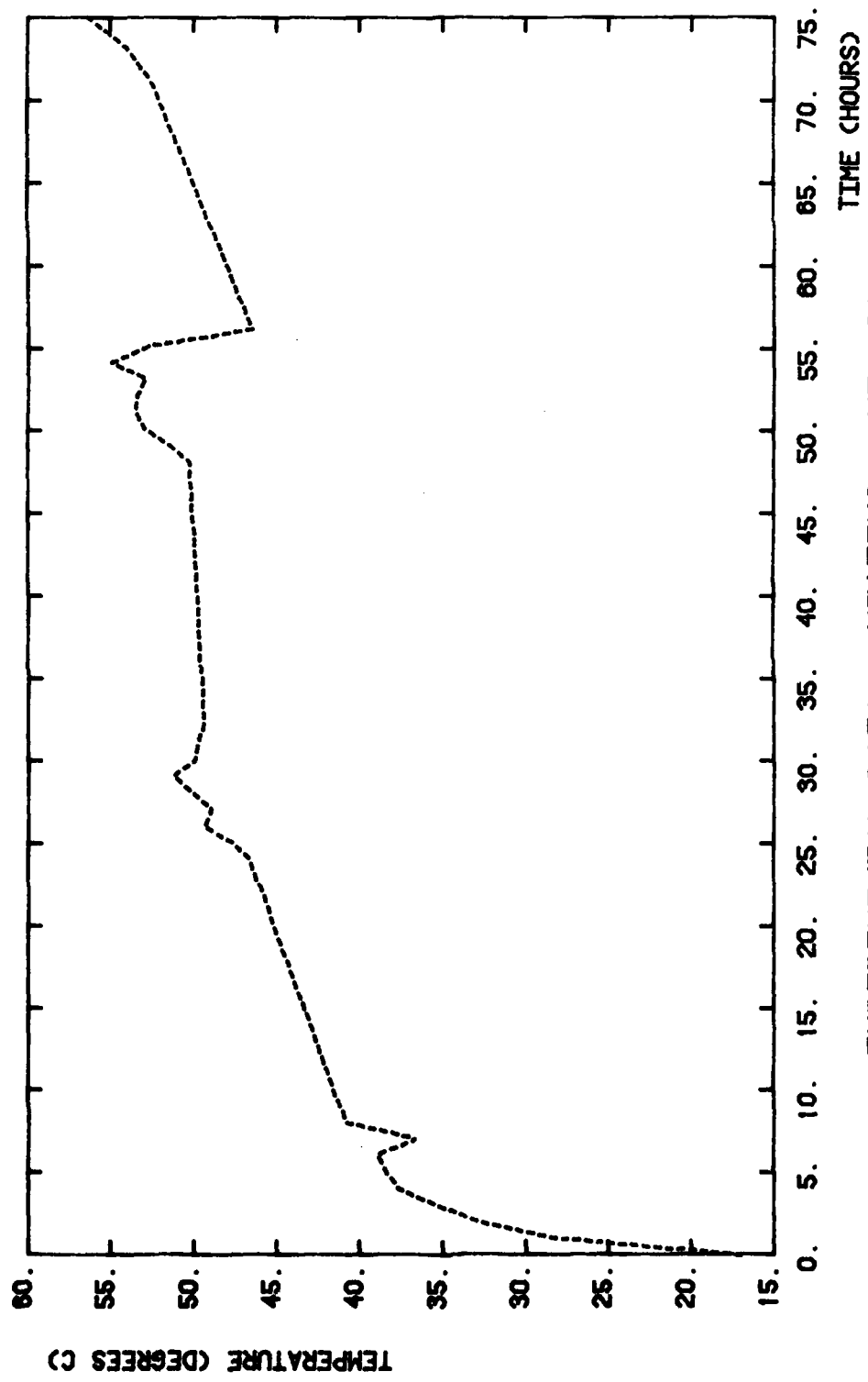


FIGURE 14



HEATING
EXPERIMENTAL DATA
FIGURE 15



EXPERIMENTAL DATA - HEATING - HT.=30.CM

FIGURE 16a

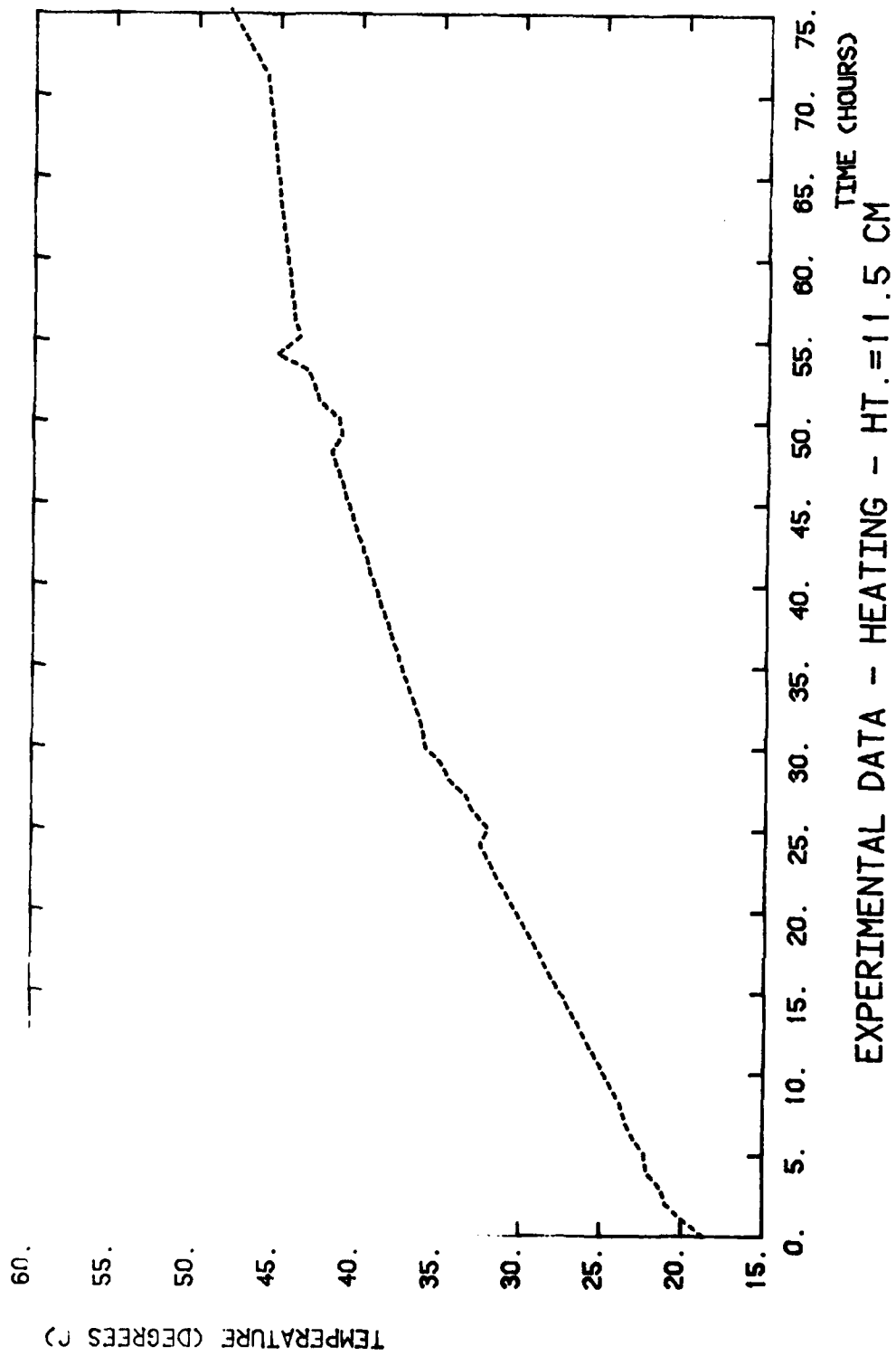


FIGURE 16b

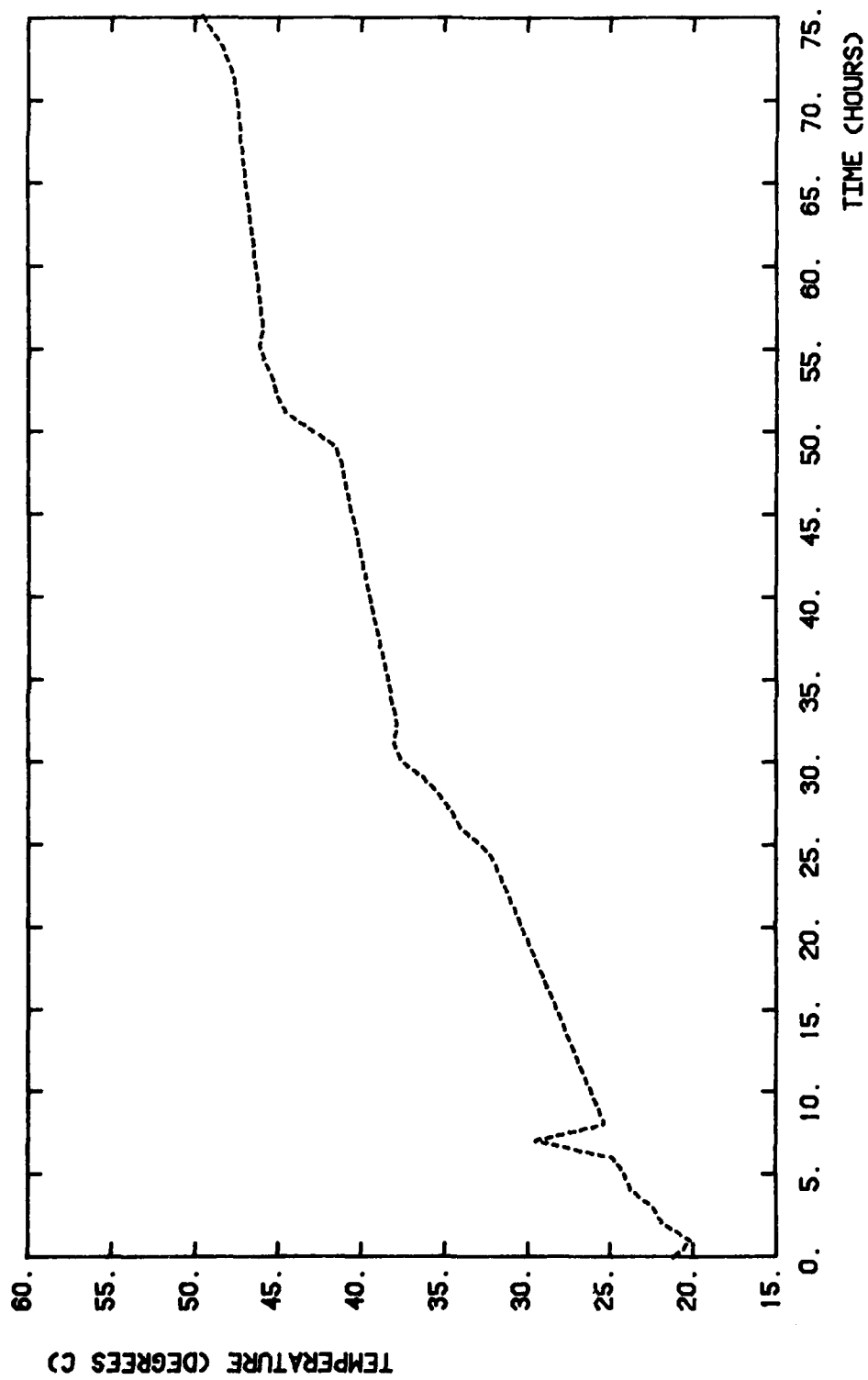
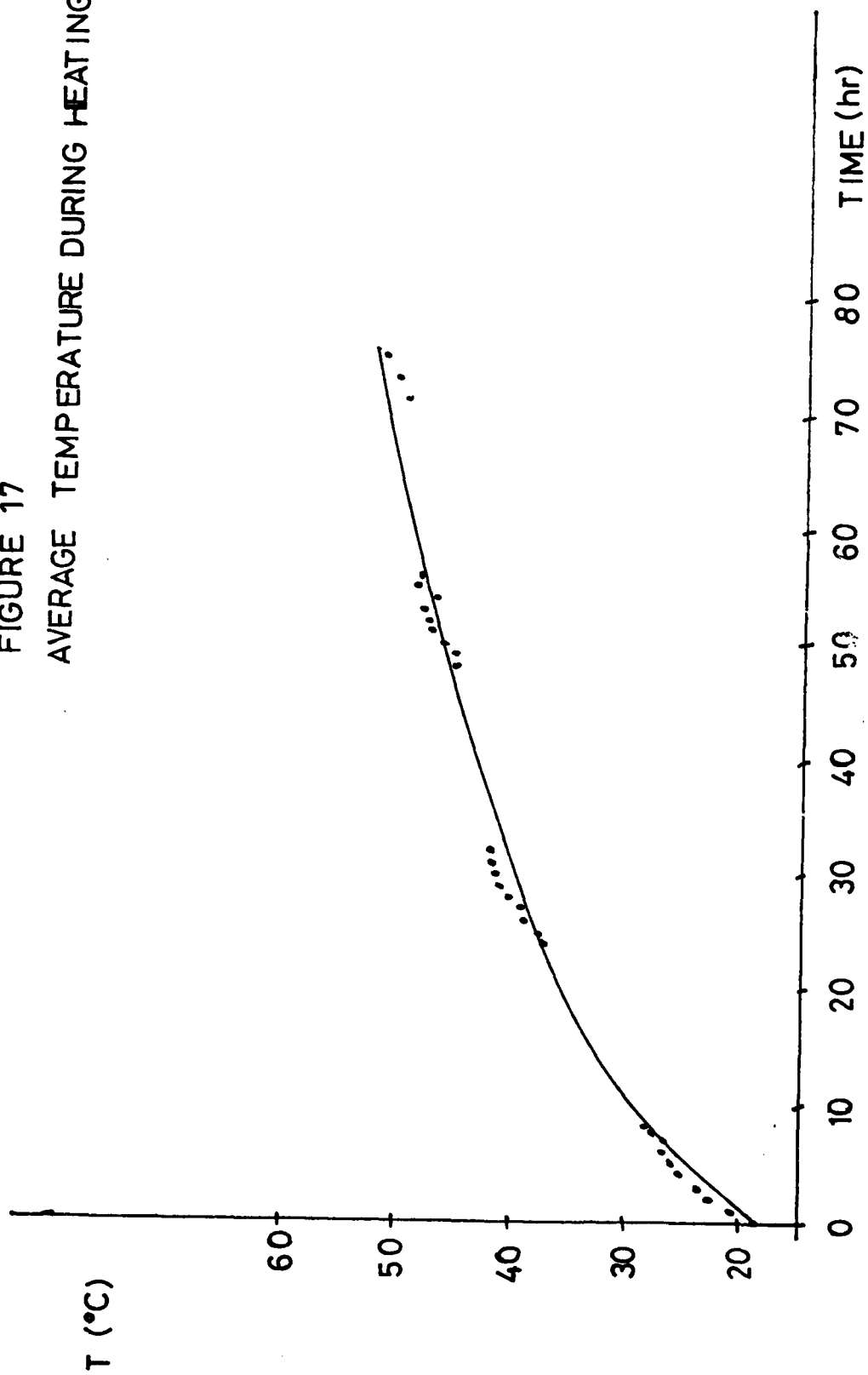


FIGURE 16c

FIGURE 17
AVERAGE TEMPERATURE DURING HEATING



$\frac{\text{heat stored}}{\text{heat input}}$

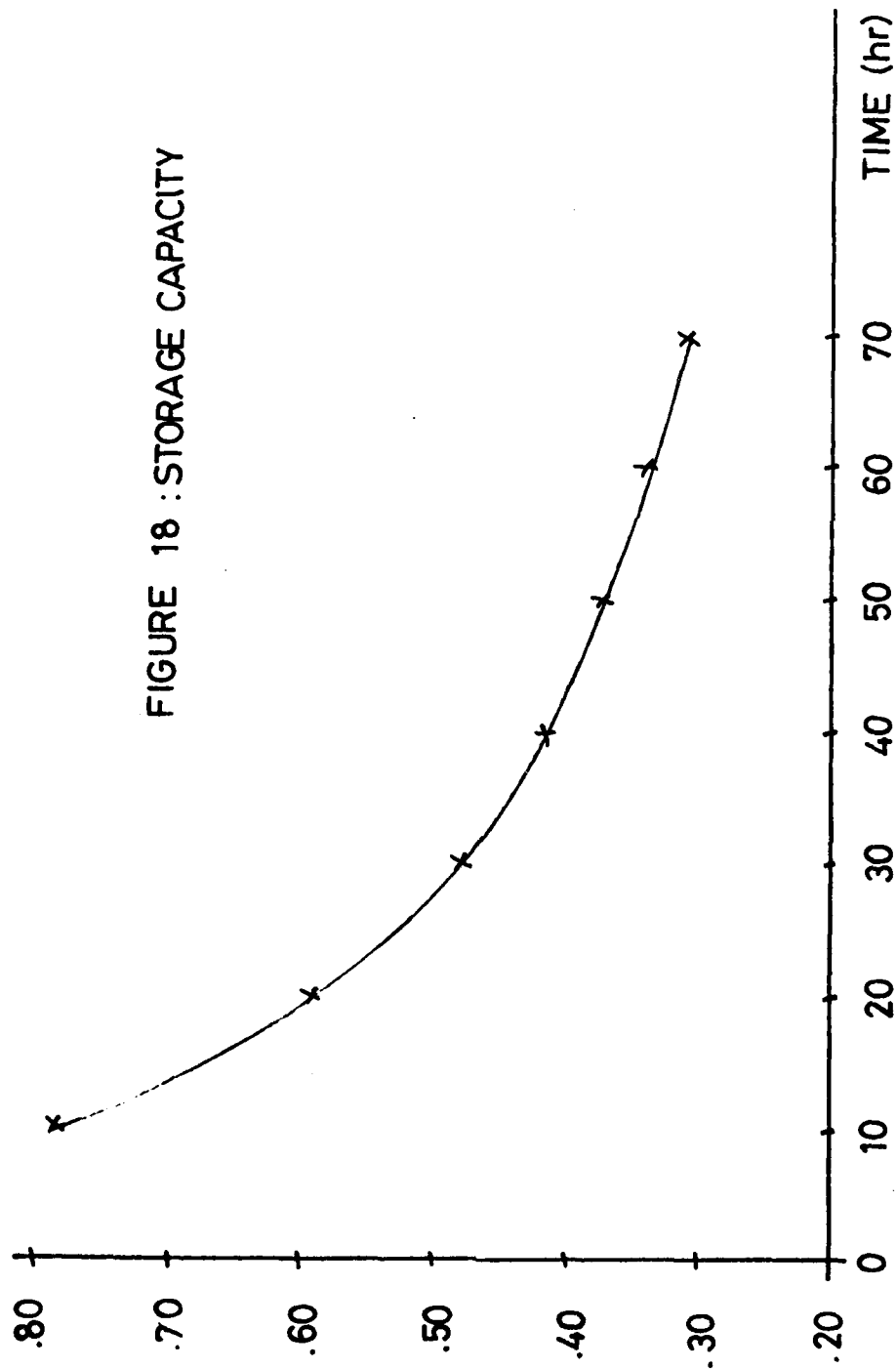
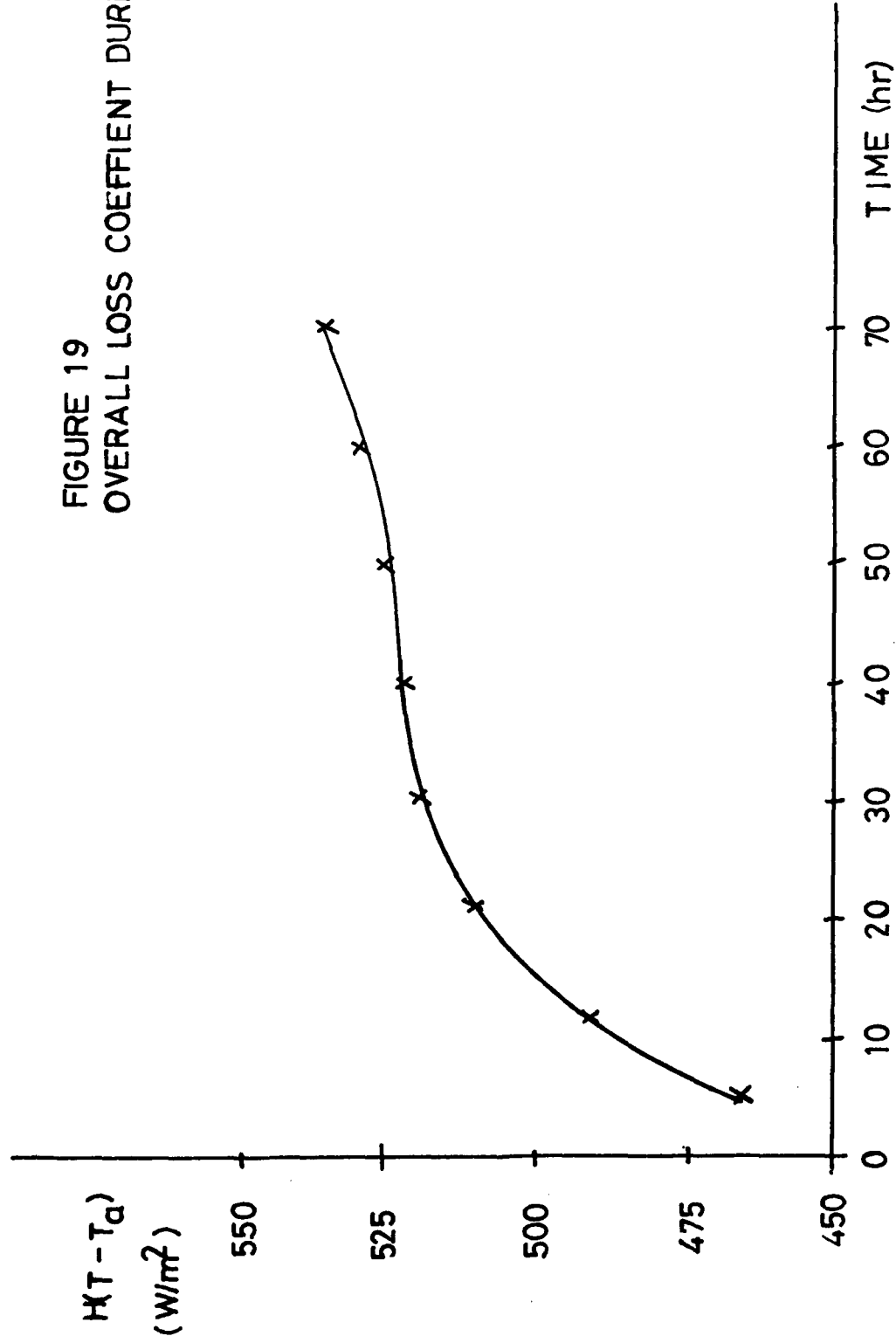
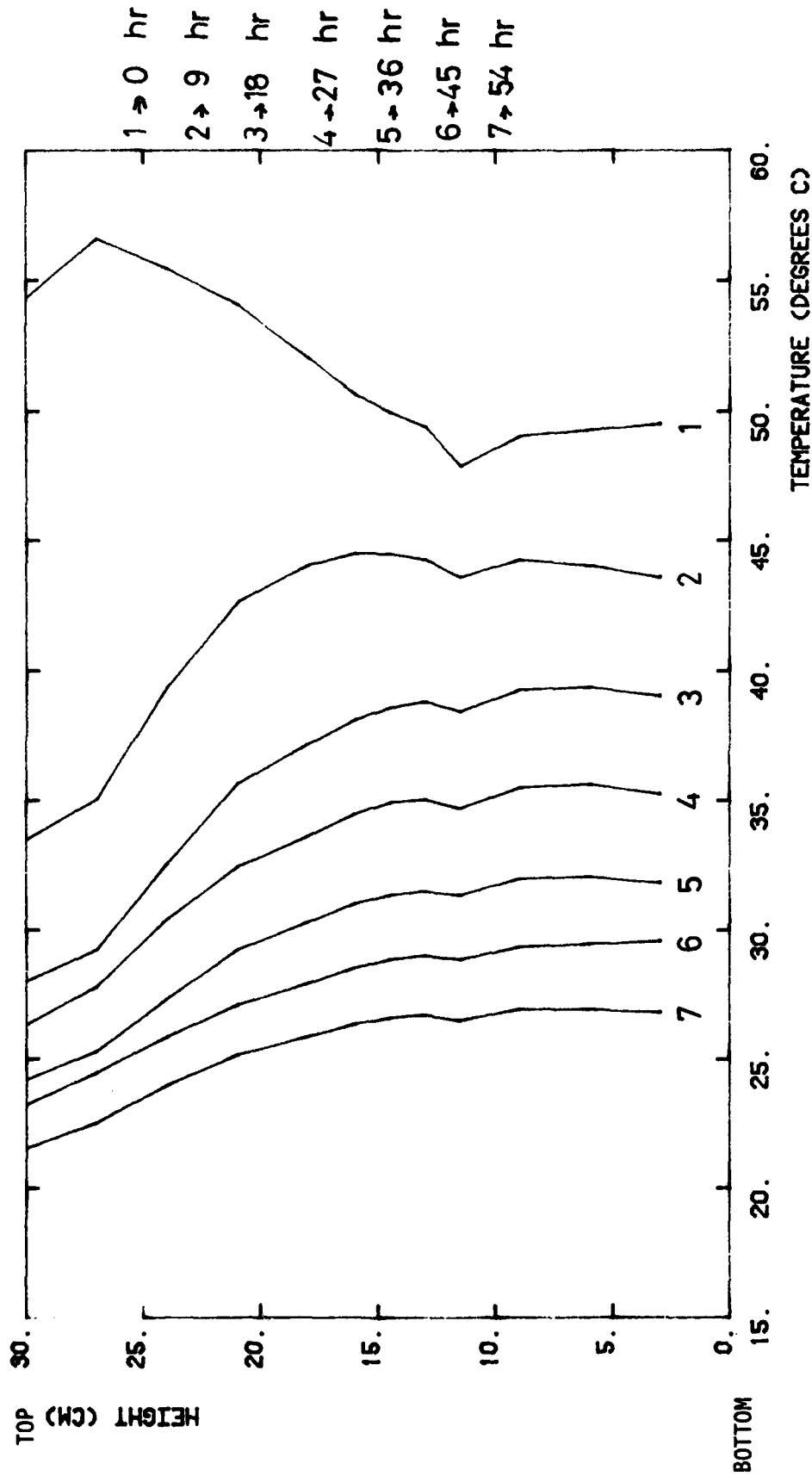


FIGURE 18 : STORAGE CAPACITY

FIGURE 19
OVERALL LOSS COEFFICIENT DURING HEATING





COOLING
EXPERIMENTAL DATA
FIGURE 20

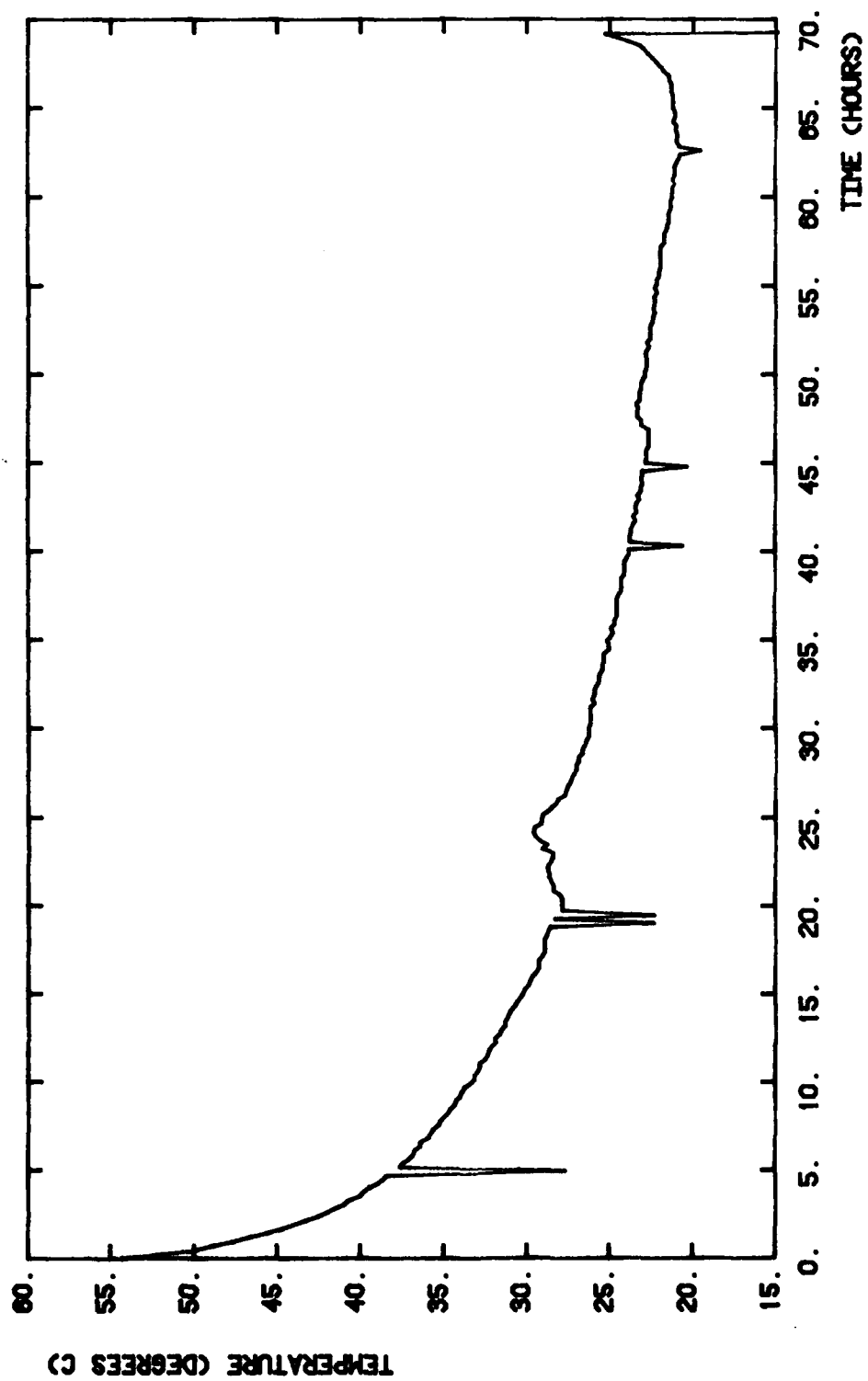


FIGURE 21a

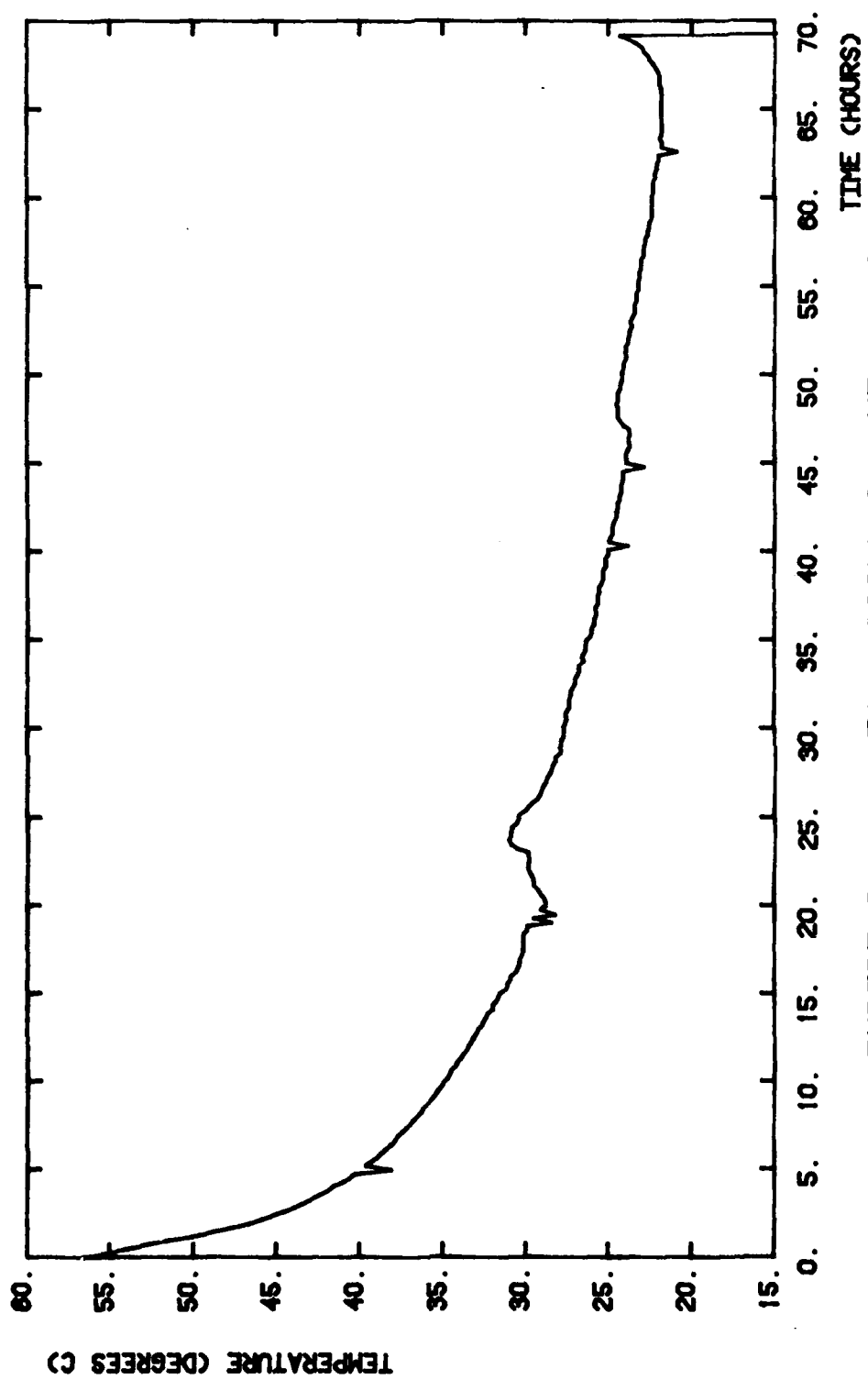


FIGURE 21b

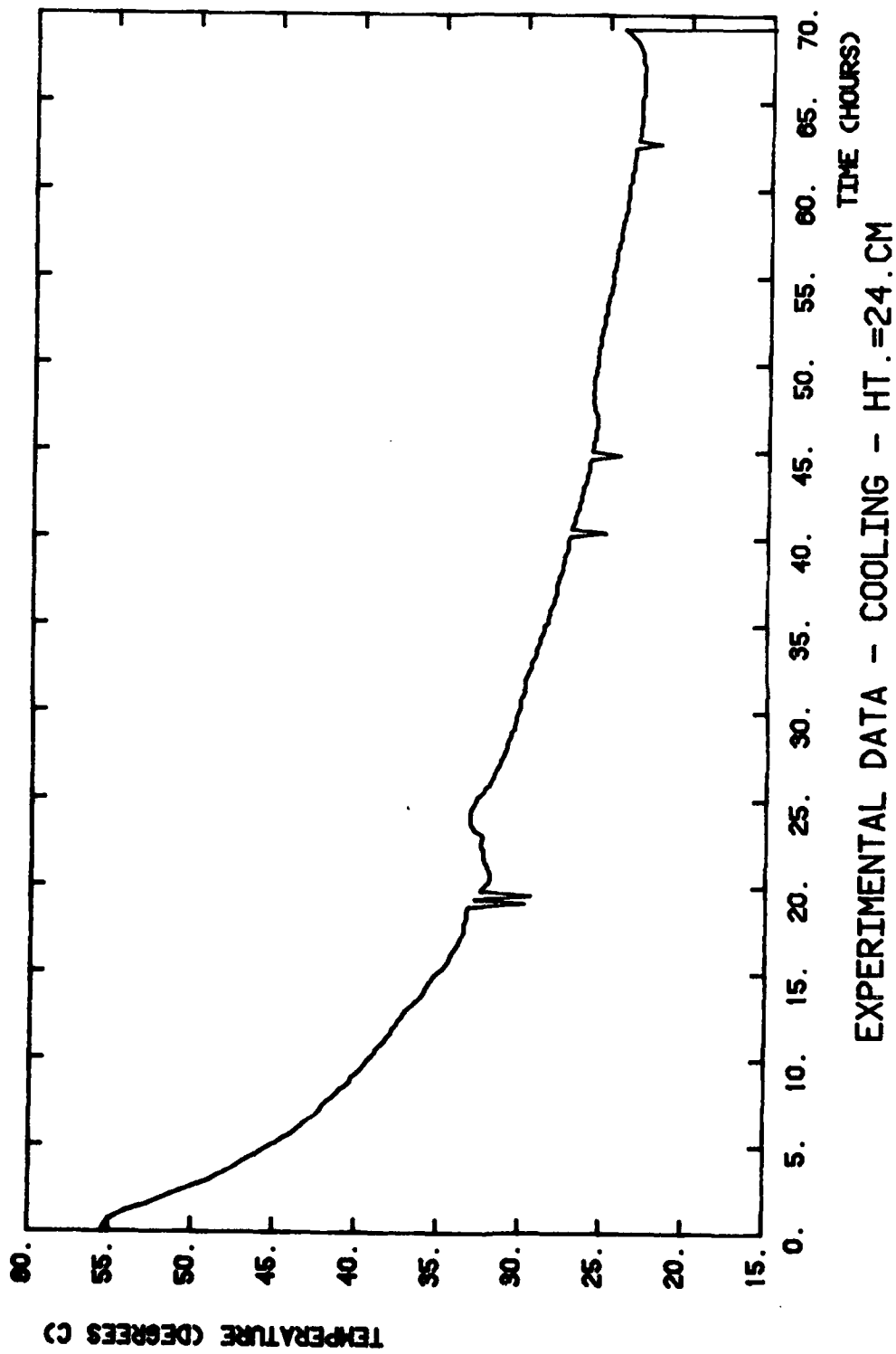


FIGURE 21c

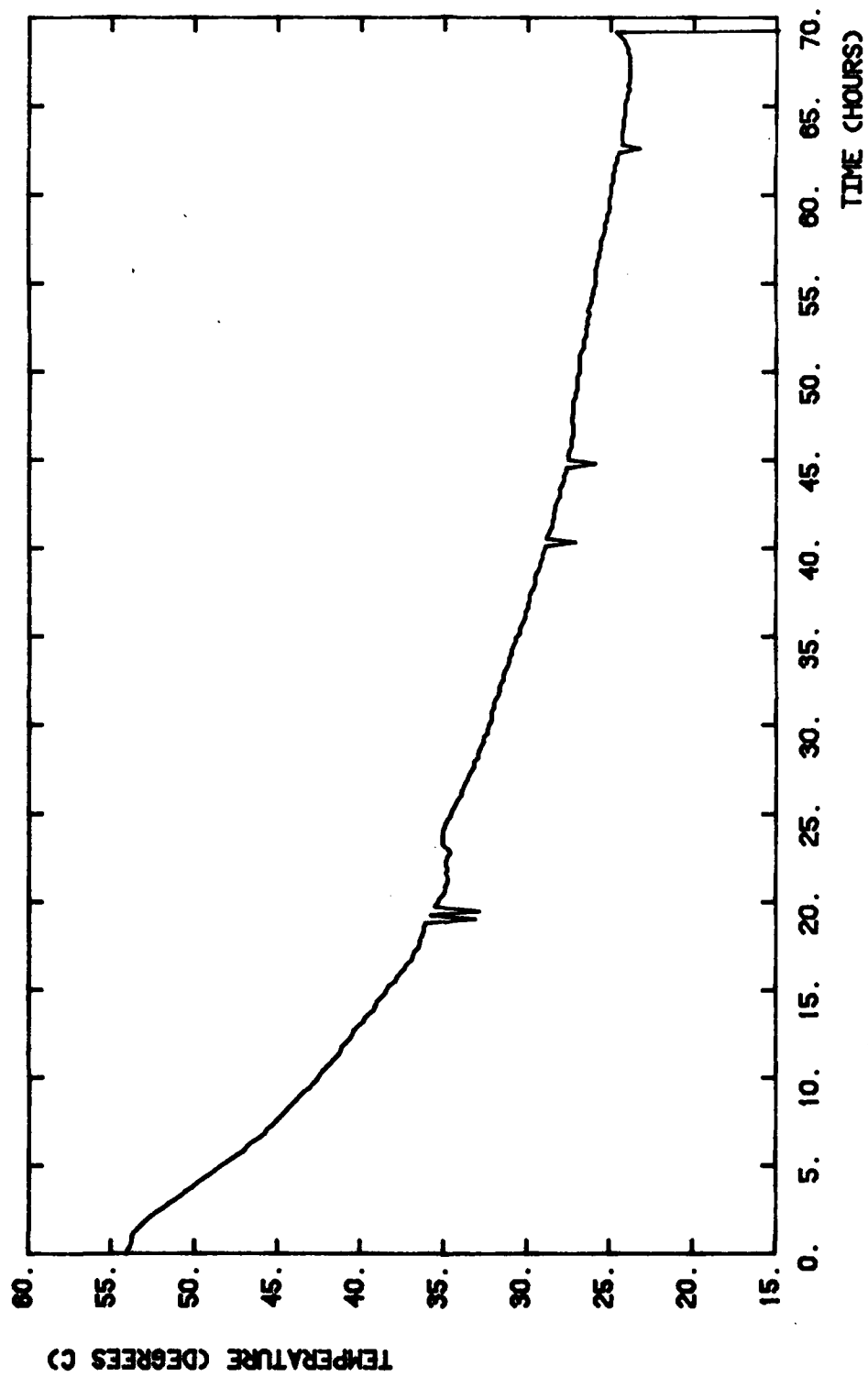
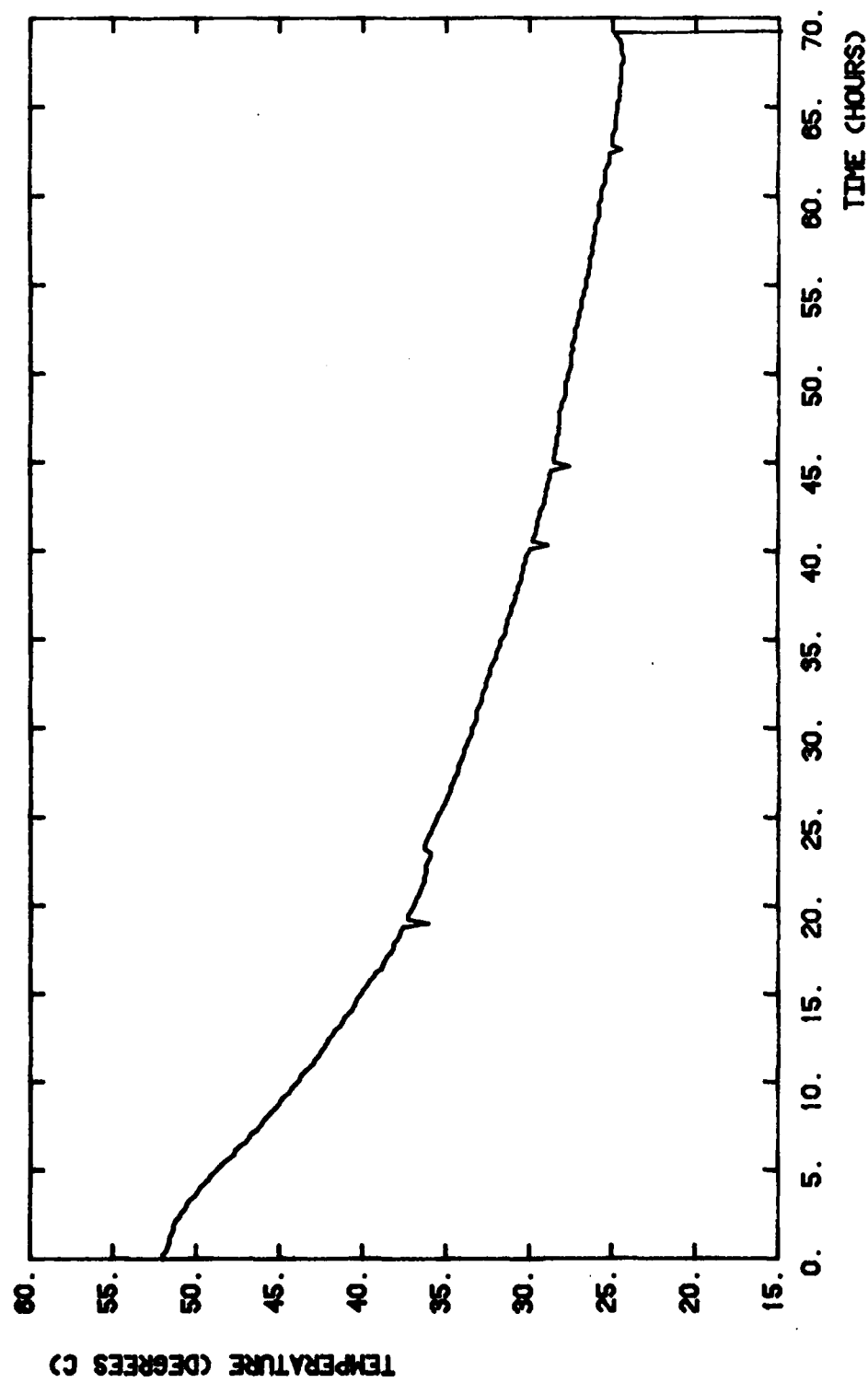
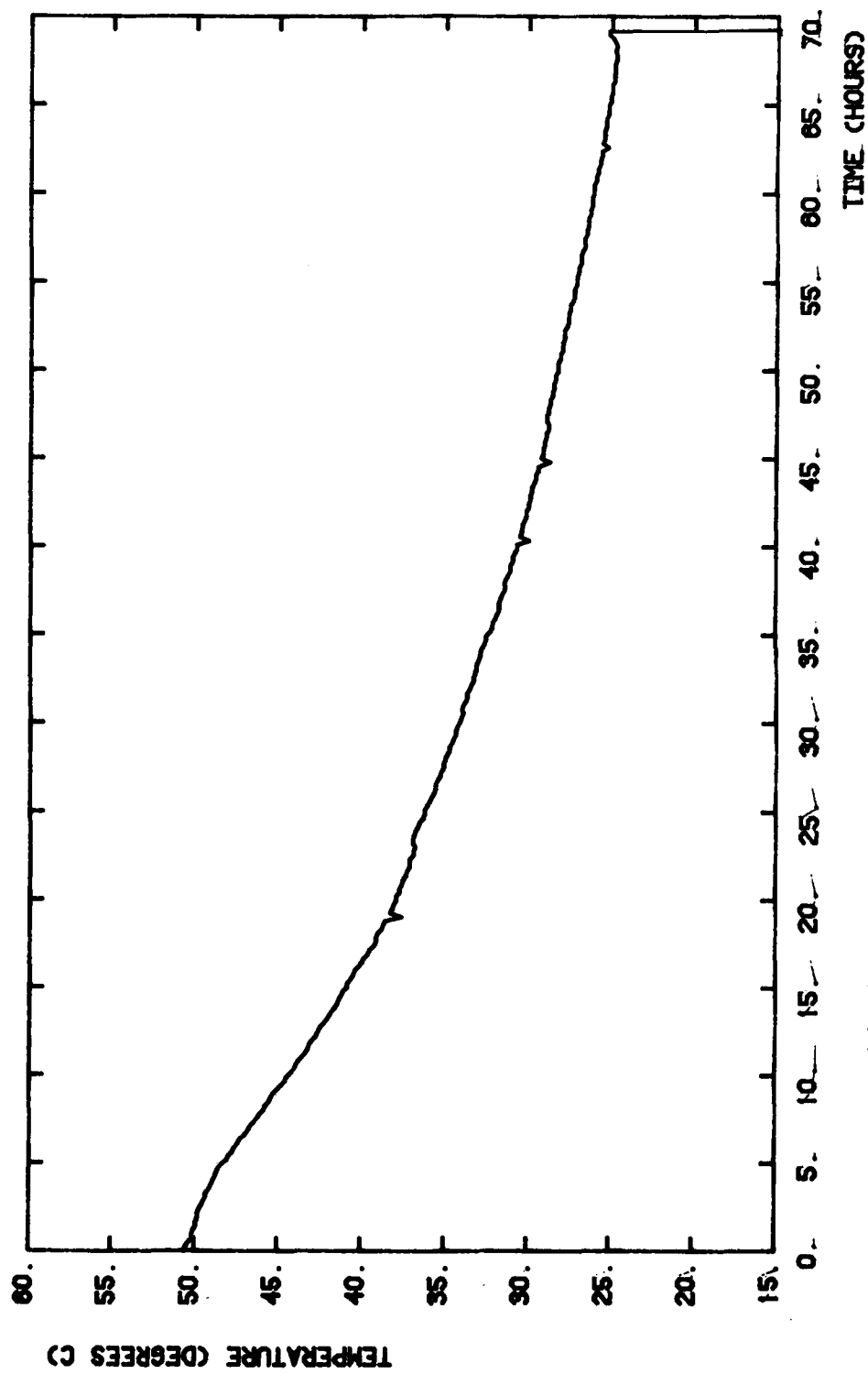


FIGURE 21d



EXPERIMENTAL DATA - COOLING - HT. = 18. CM

FIGURE 21e



EXPERIMENTAL DATA -- COOLING -- HT. = 16 CM

FIGURE 21f

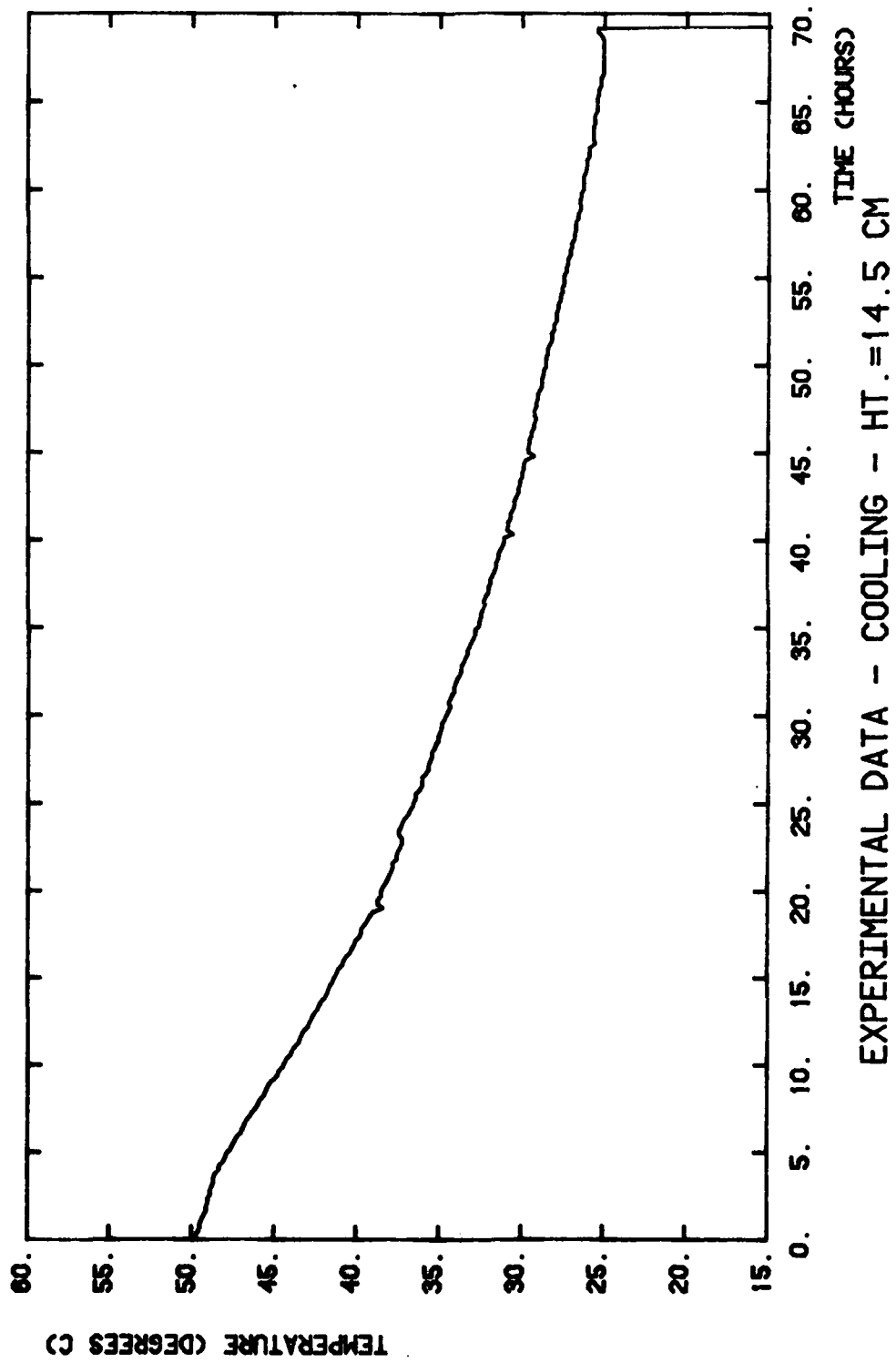


FIGURE 21g

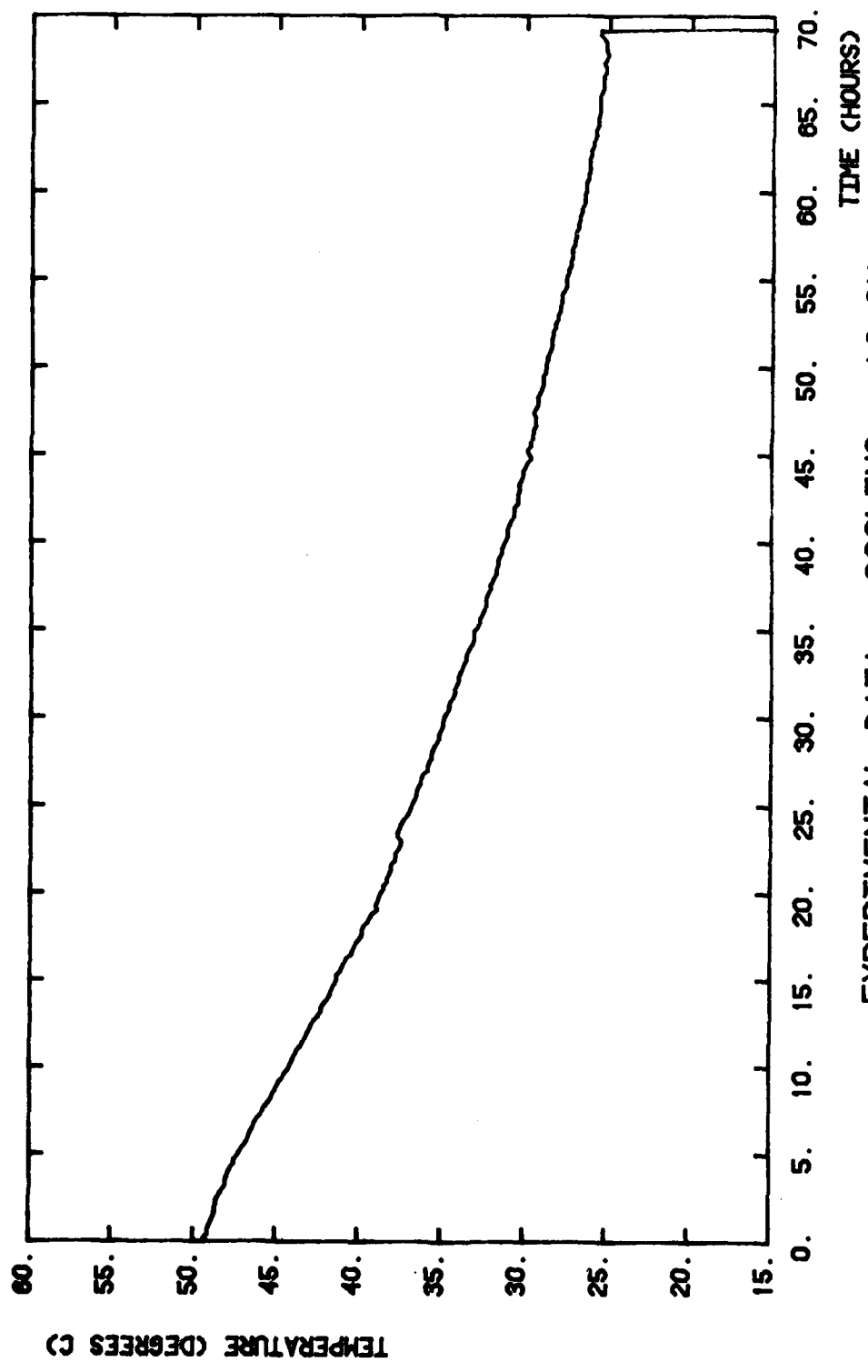


FIGURE 21h

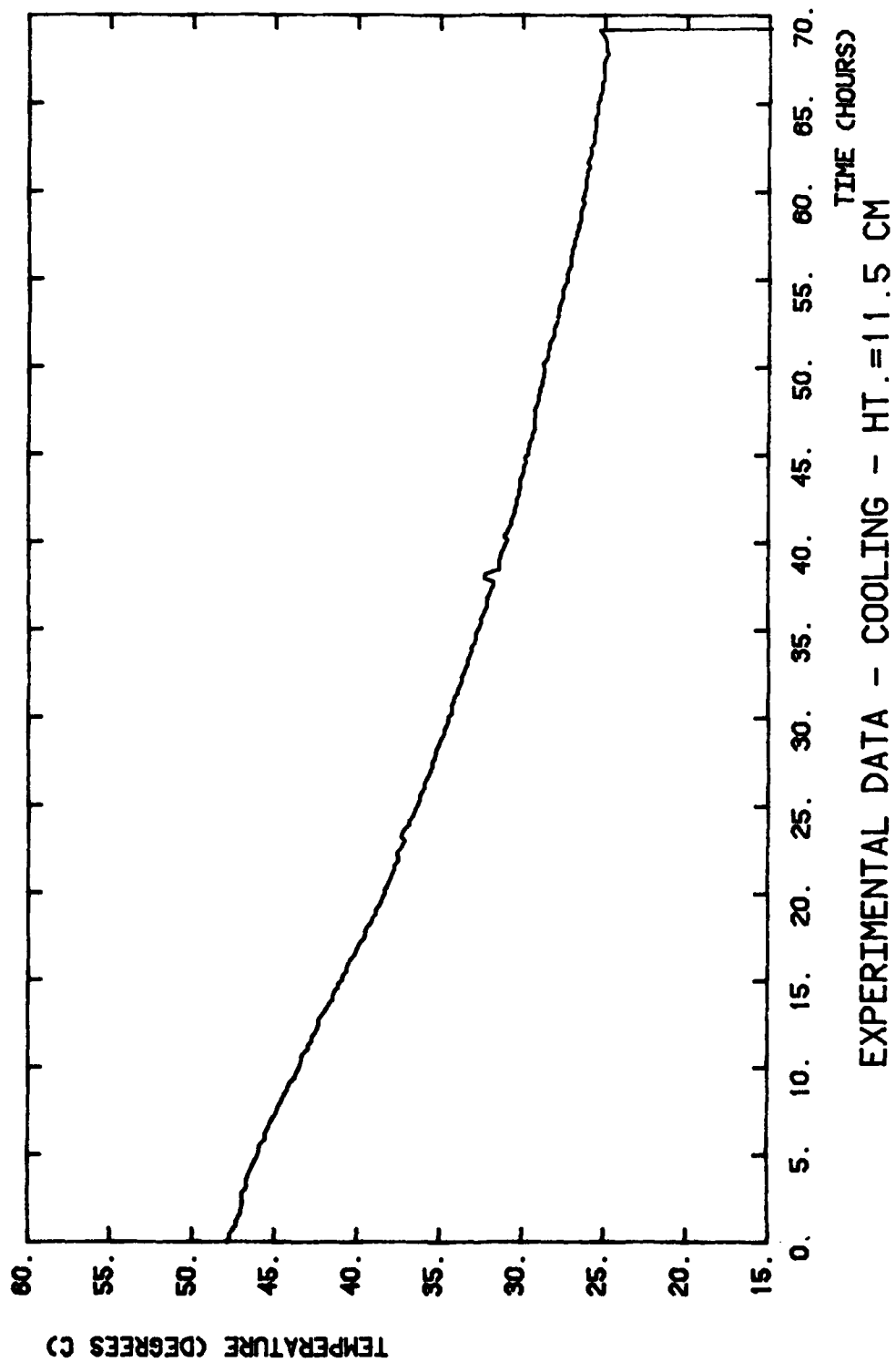


FIGURE 21i

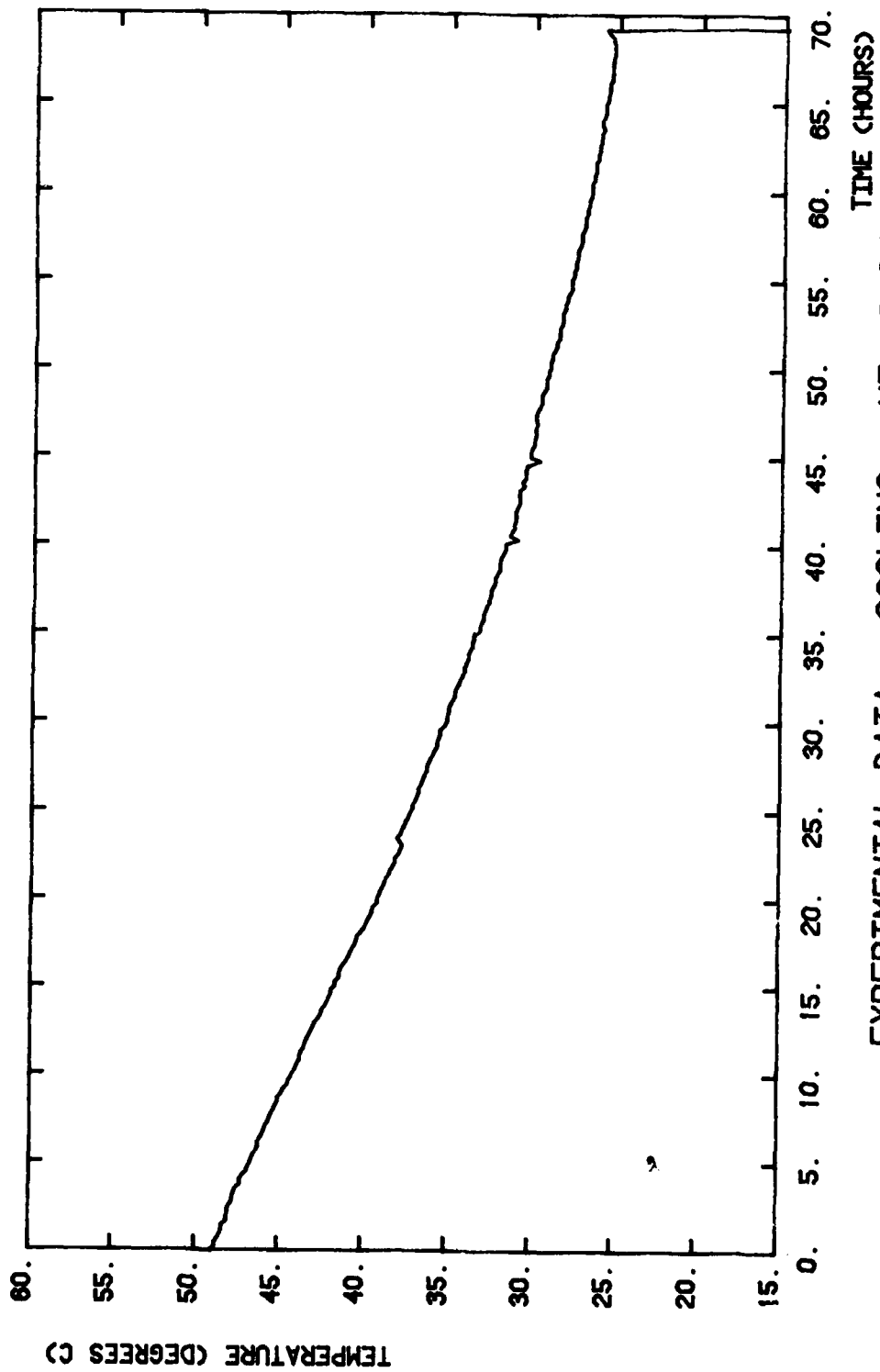


FIGURE 21j

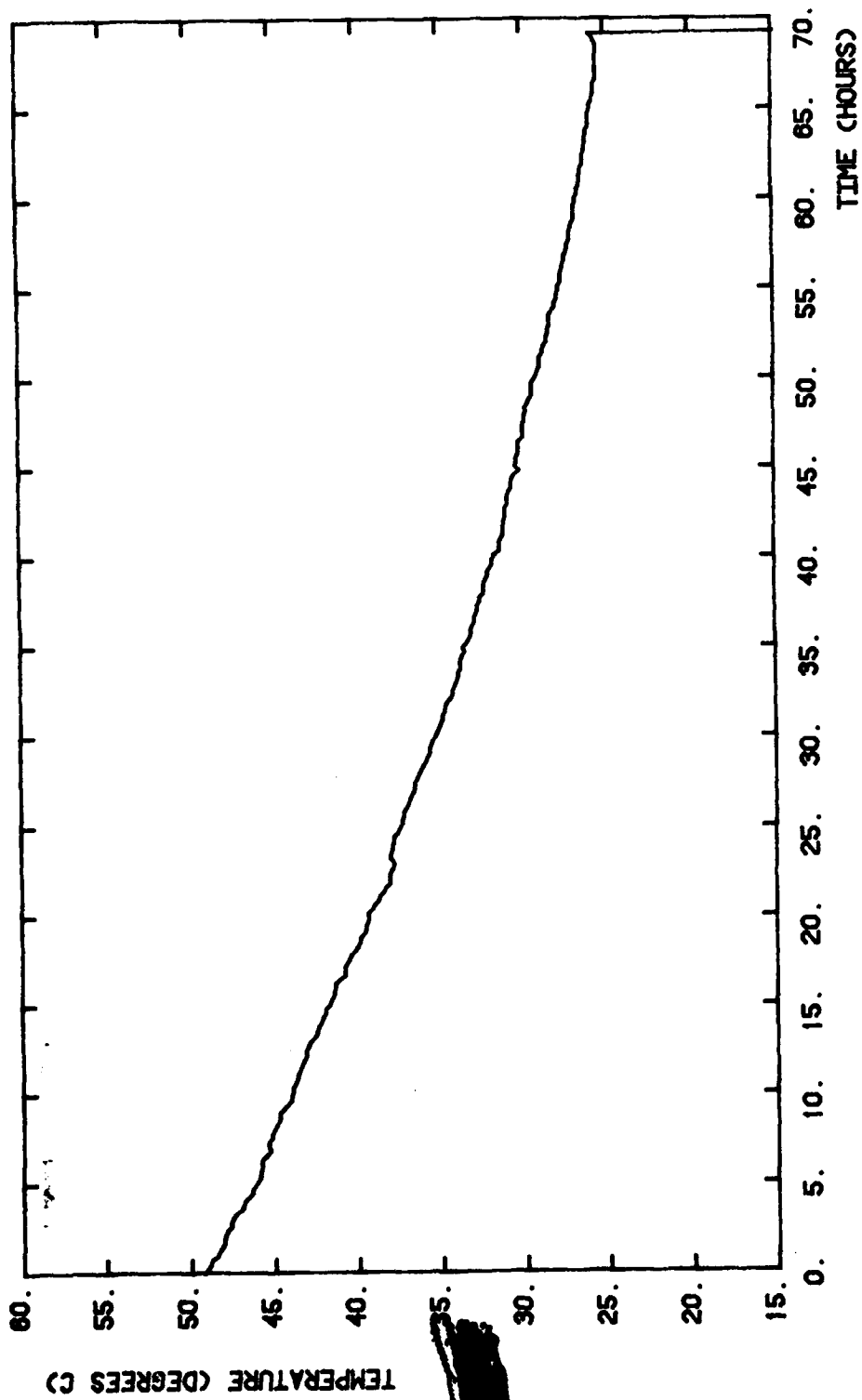


FIGURE 21k

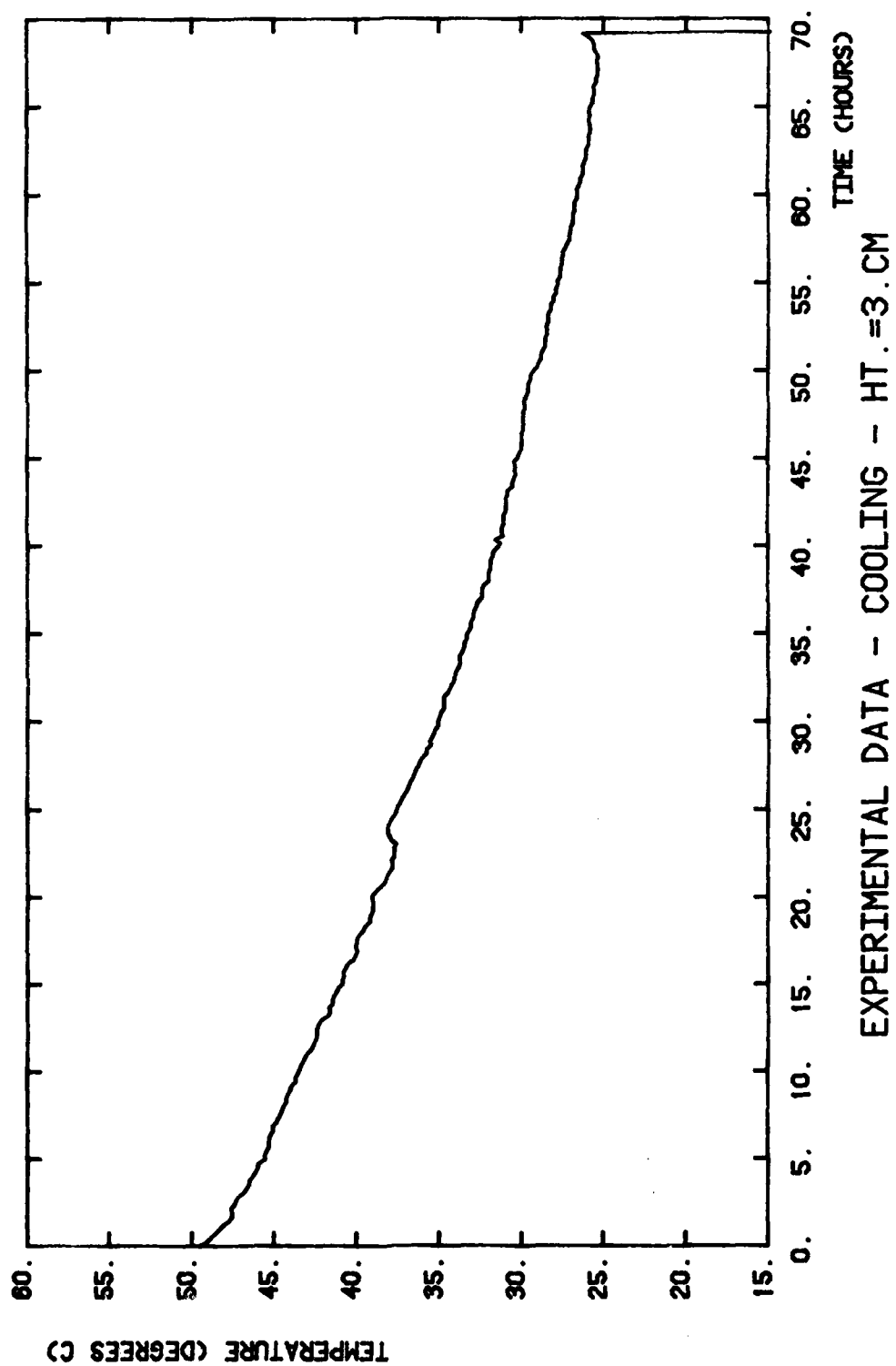
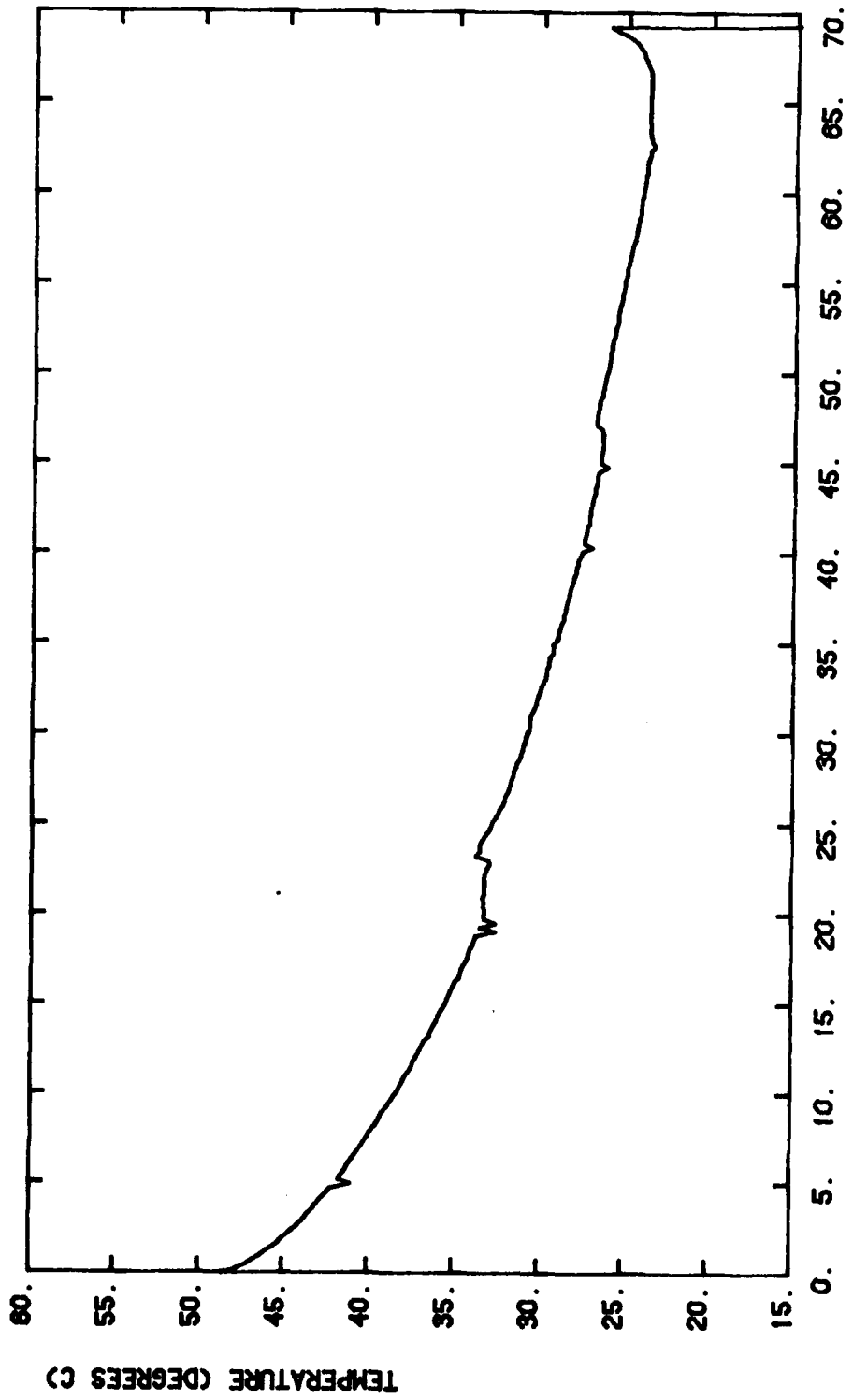
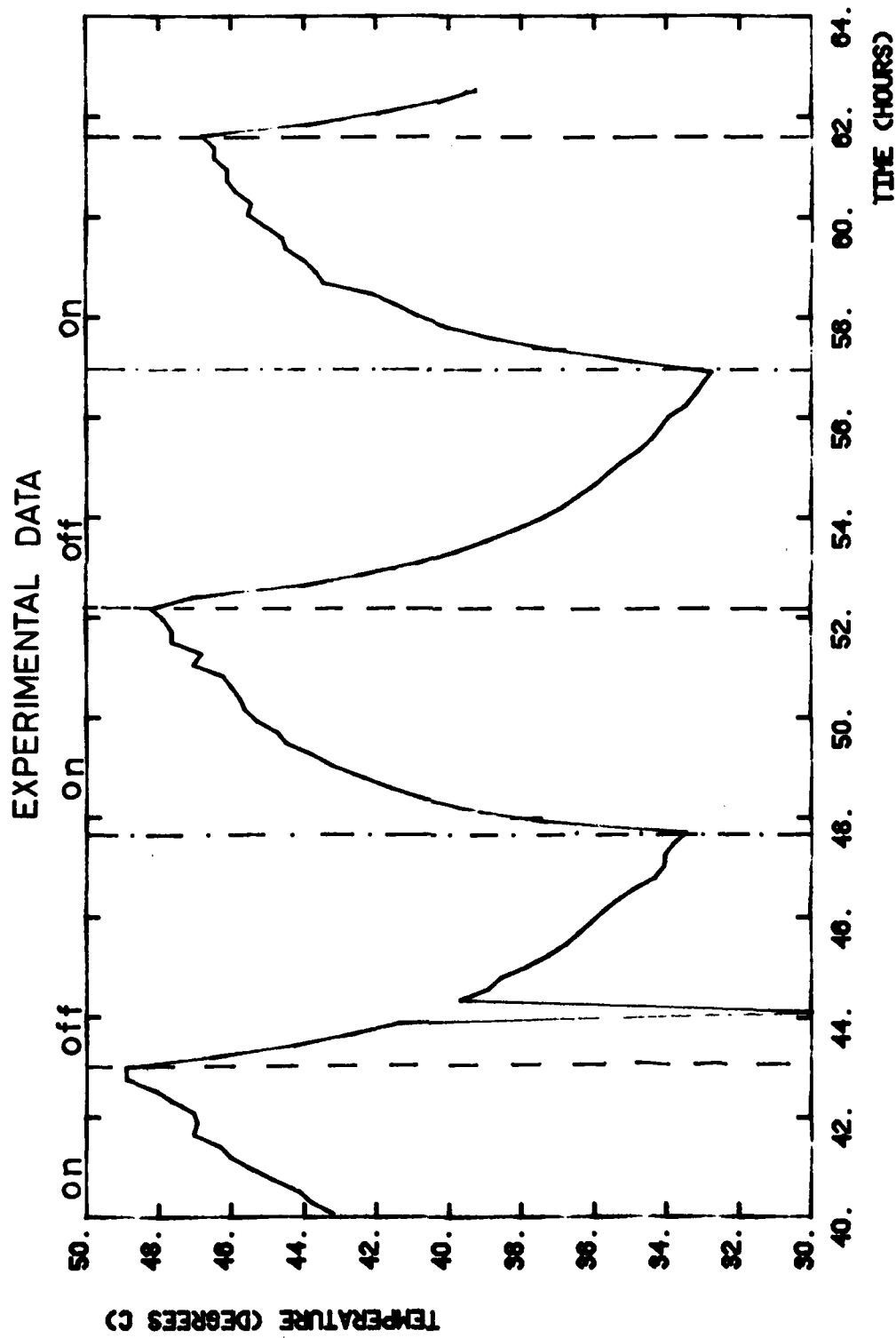


FIGURE 21I



EXPERIMENTAL DATA - COOLING - AVERAGE TEMPERATURE

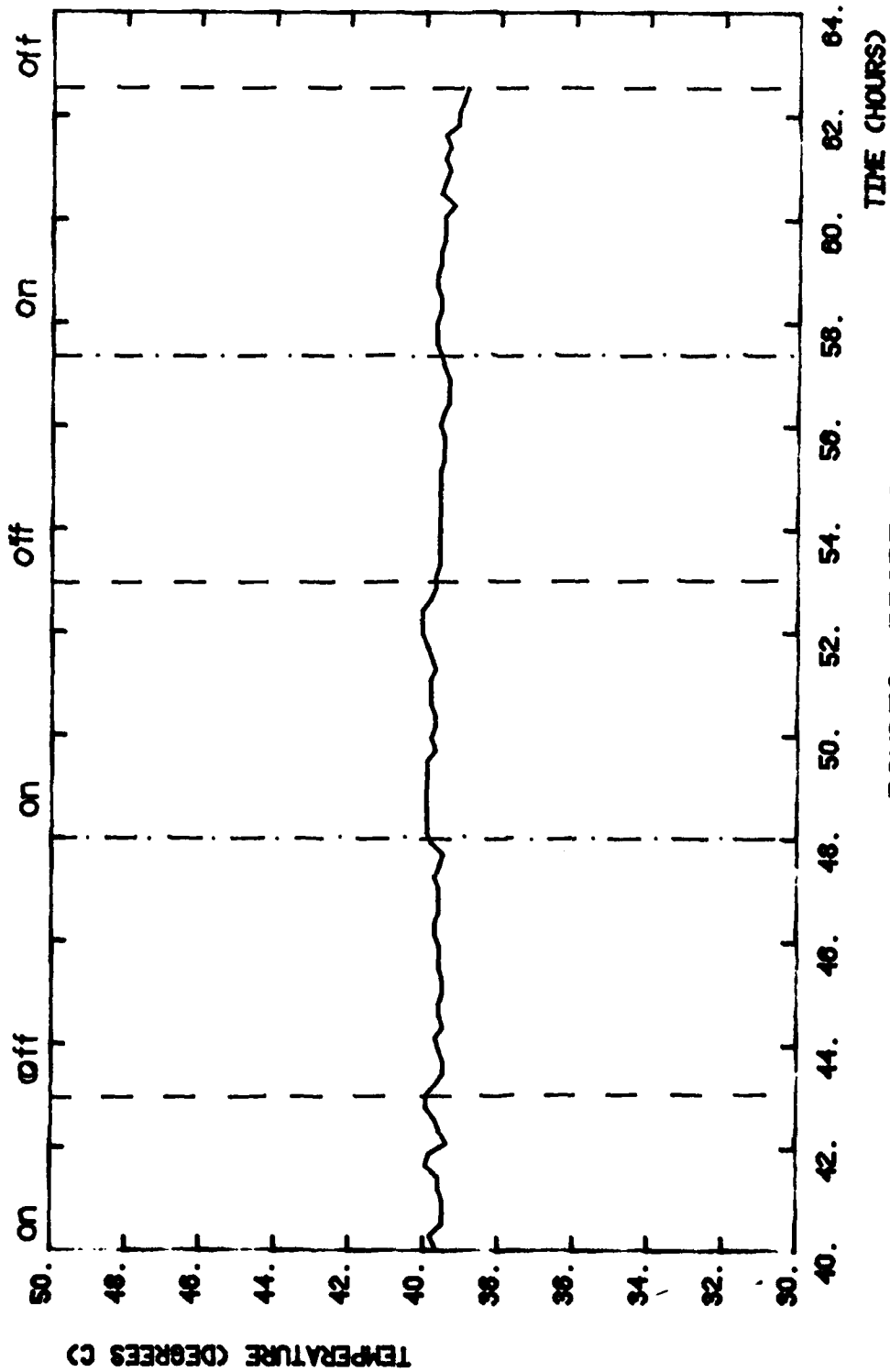
FIGURE 22



POND58, PROBE 12

POND SURFACE

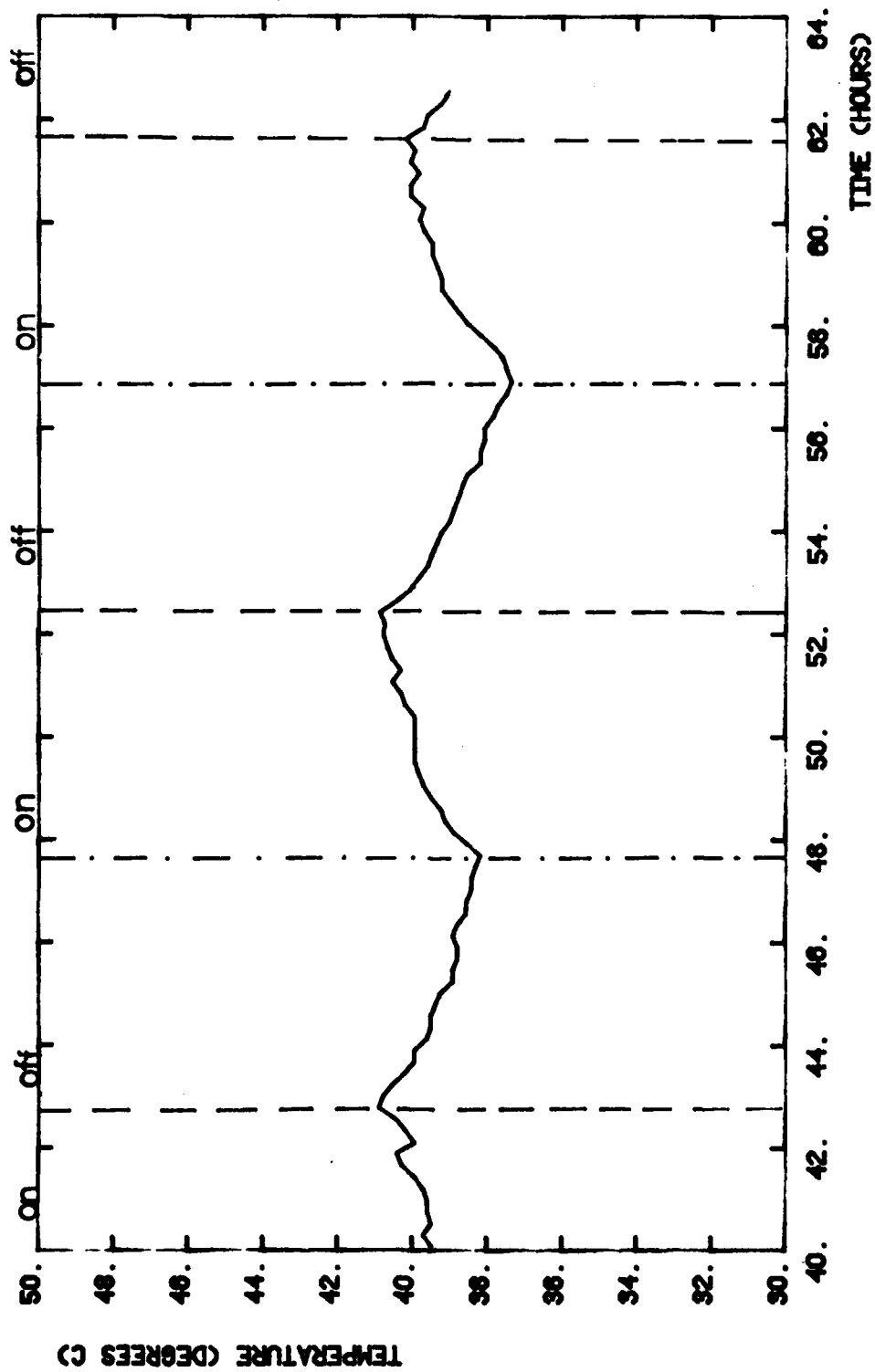
FIGURE 23a



POND58, PROBE 6

BOTTOM OF NCZ

FIGURE 23b



POND58, PROBE 1

POND BOTTOM

FIGURE 23c

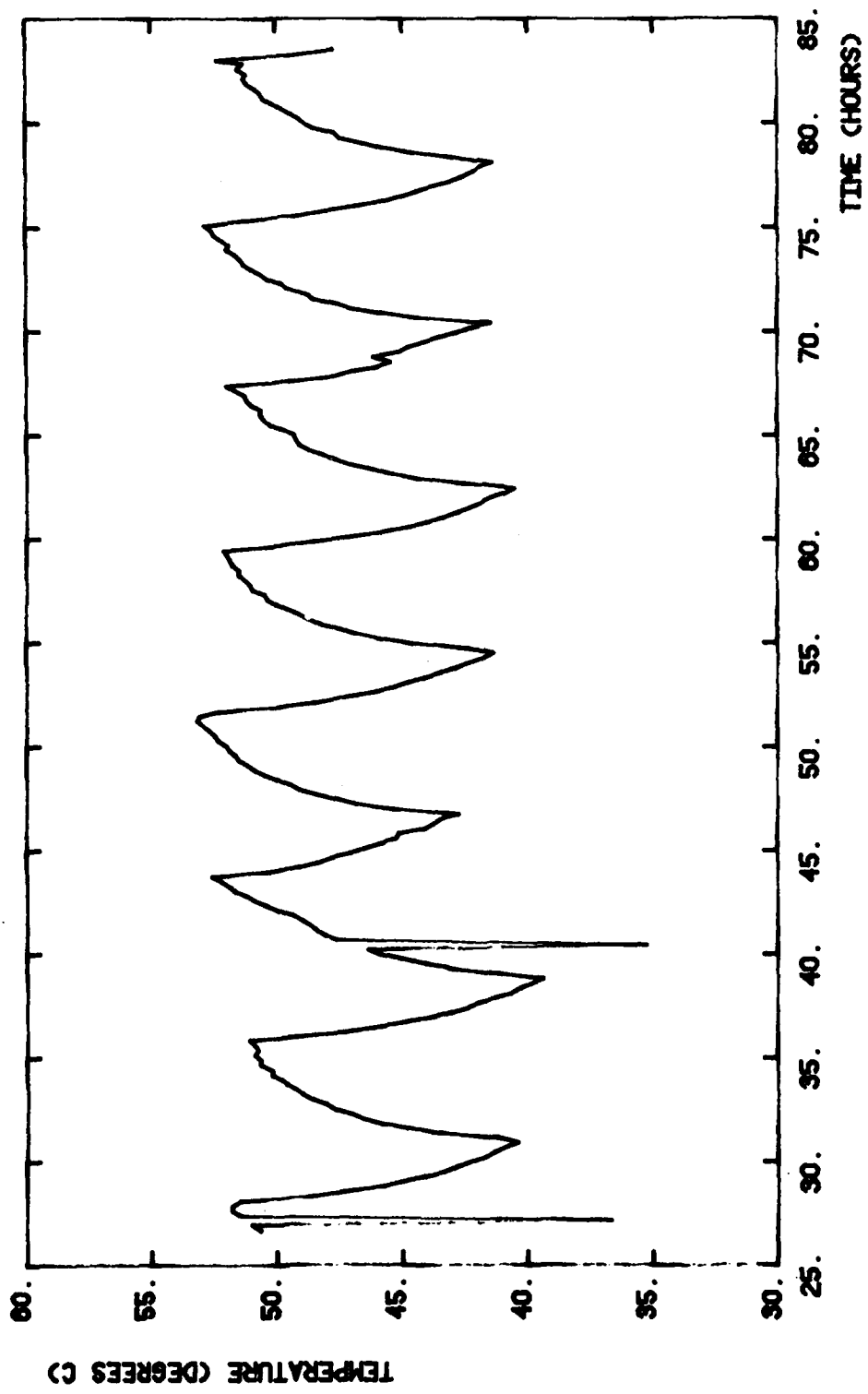


FIGURE 24a

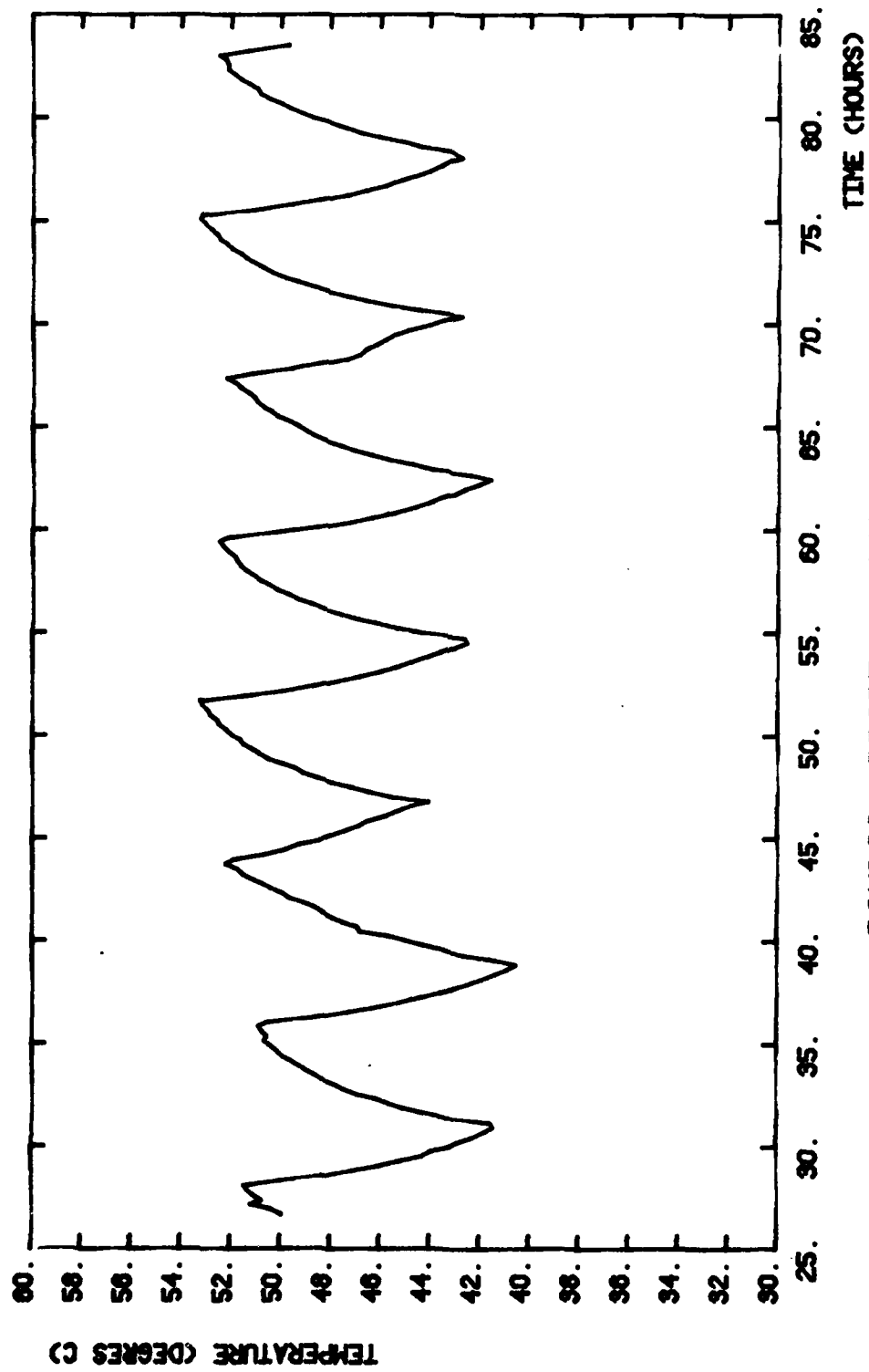


FIGURE 24b

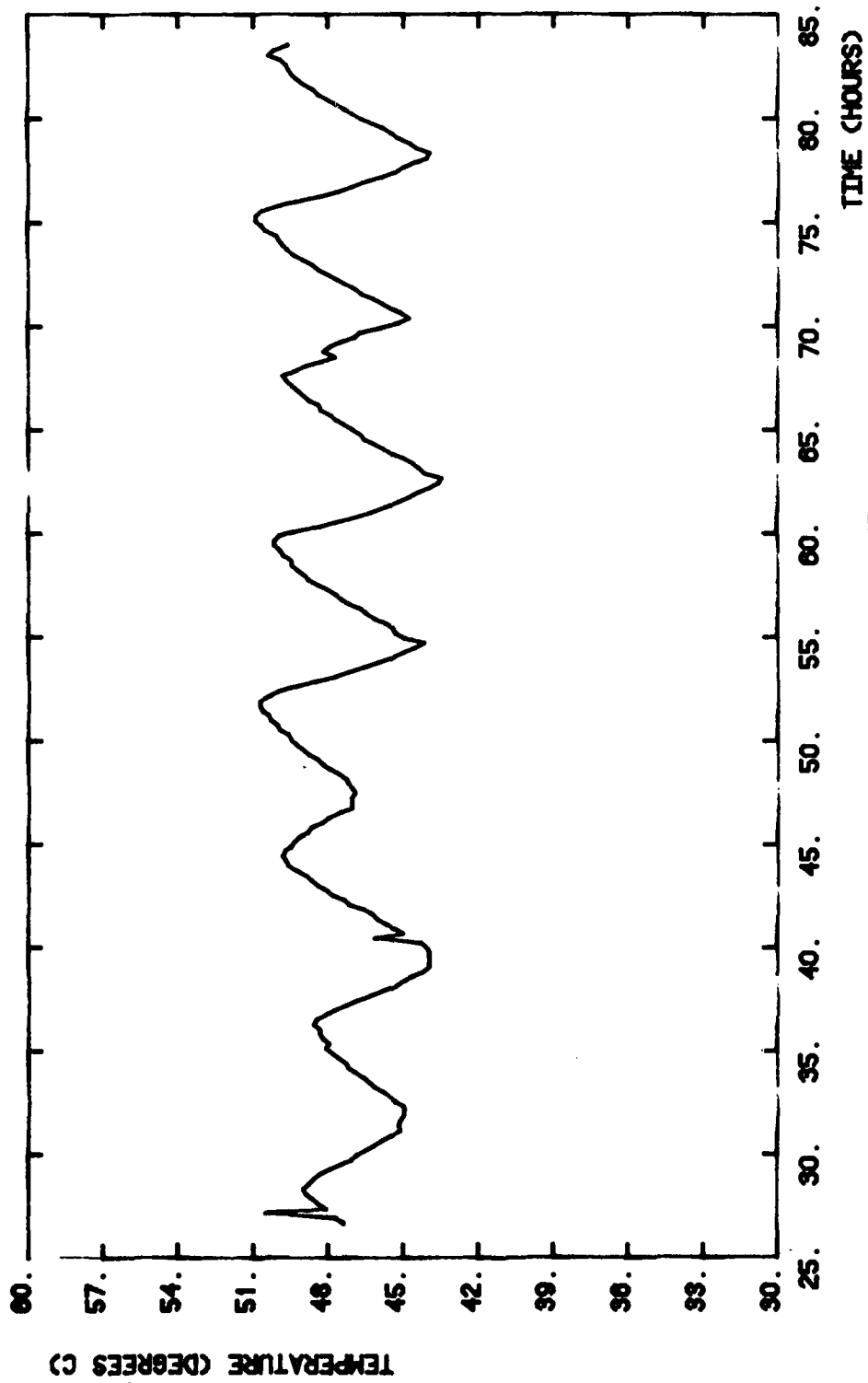


FIGURE 24c

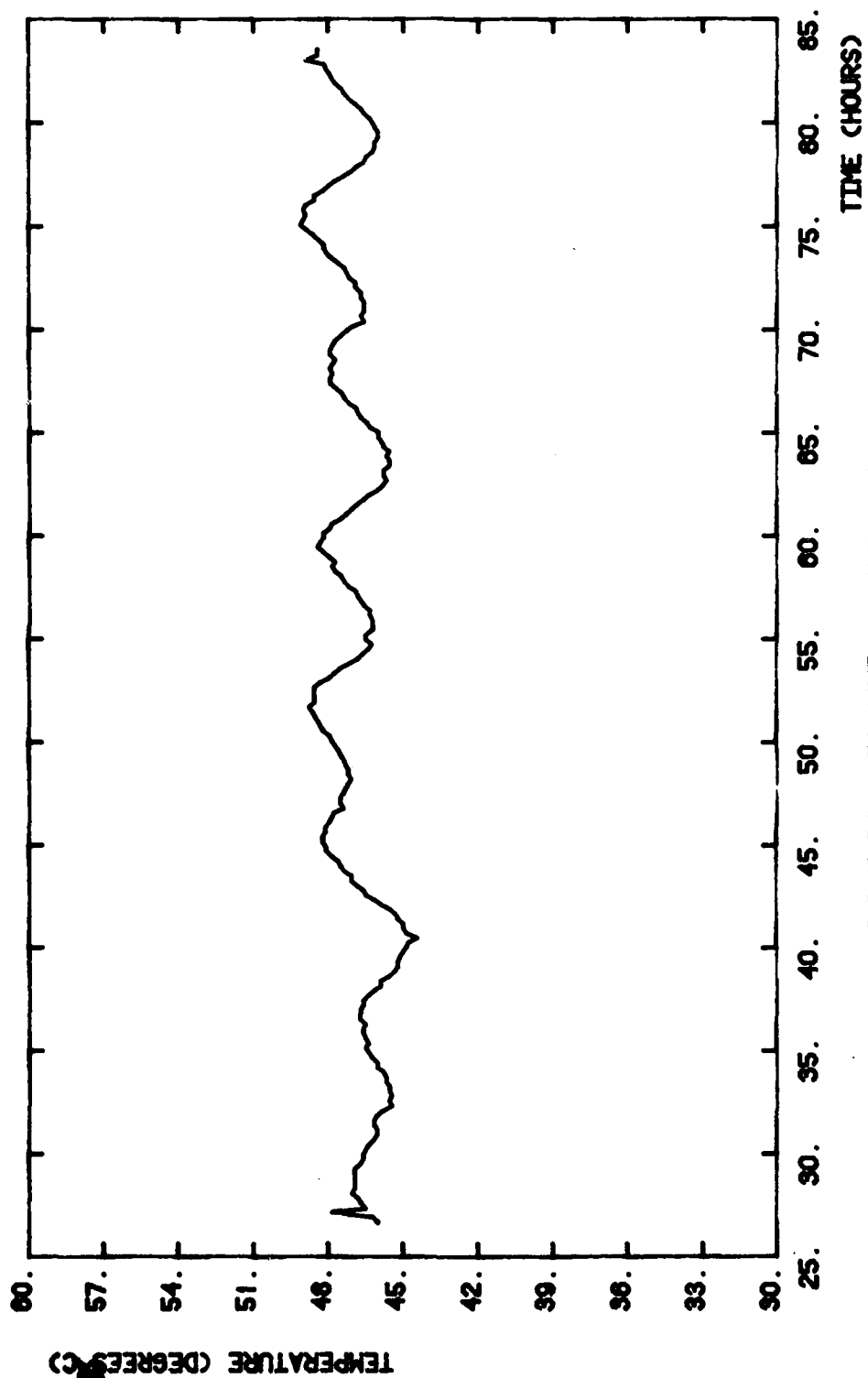


FIGURE 24d

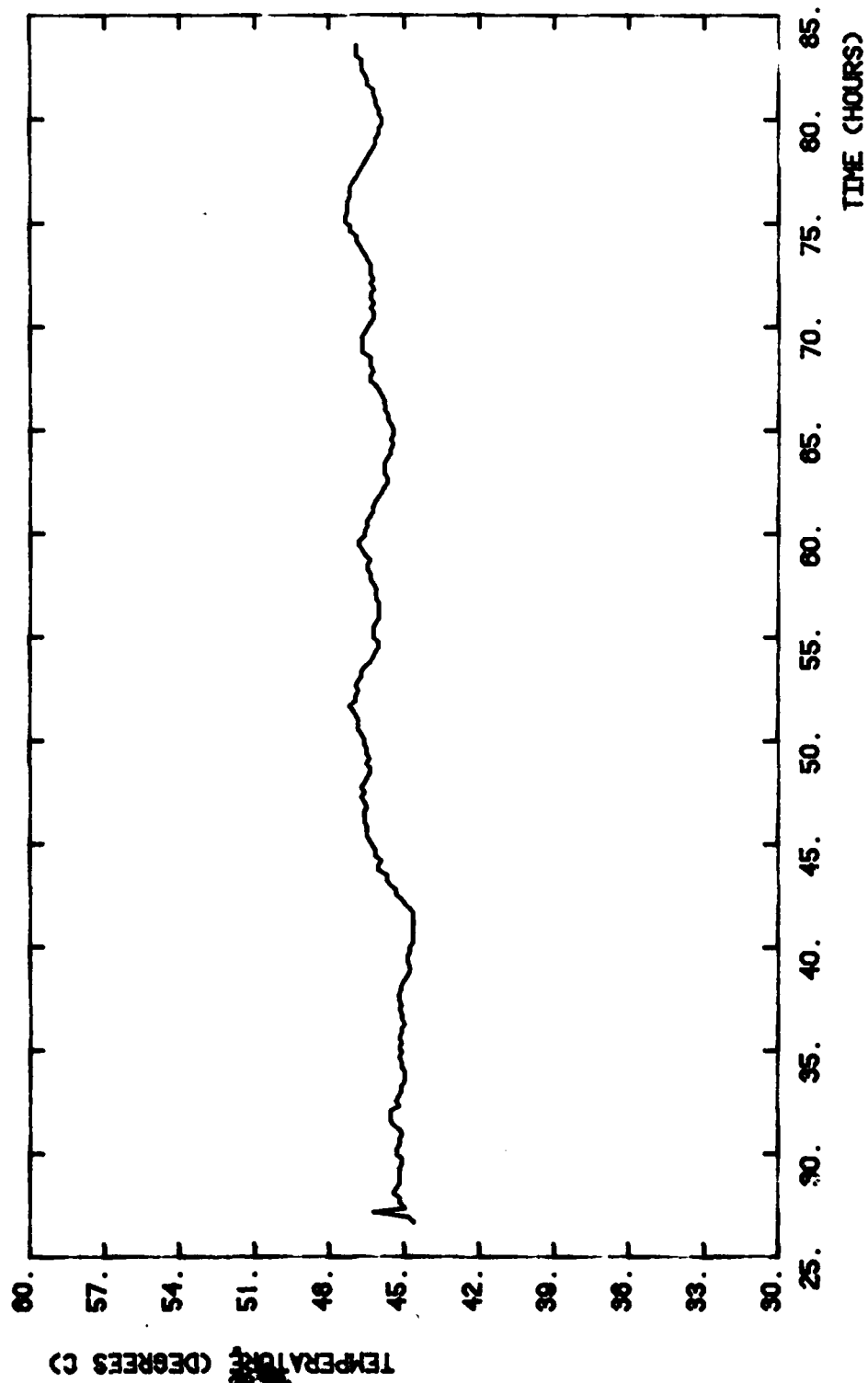


FIGURE 24e

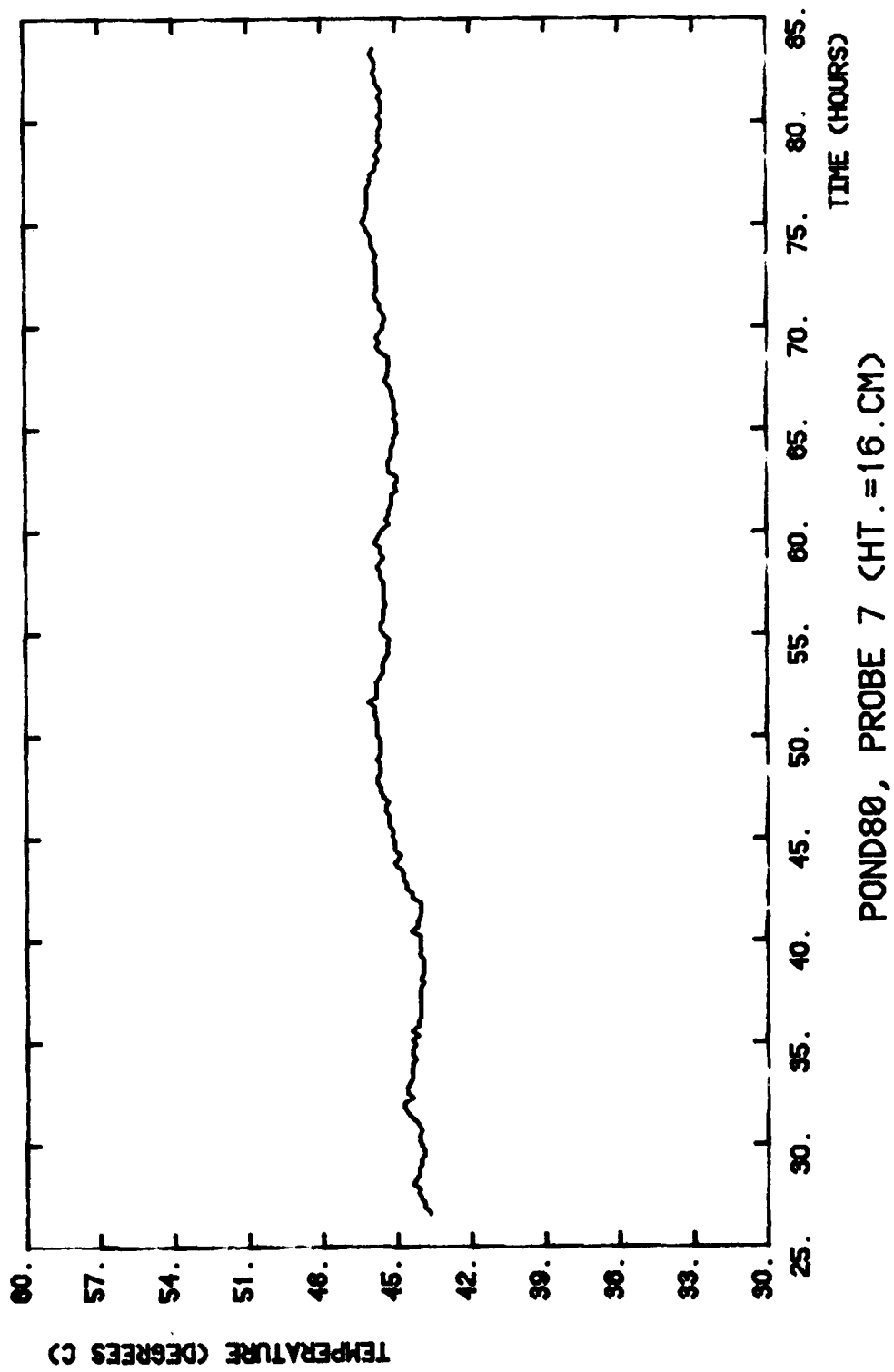


FIGURE 24f

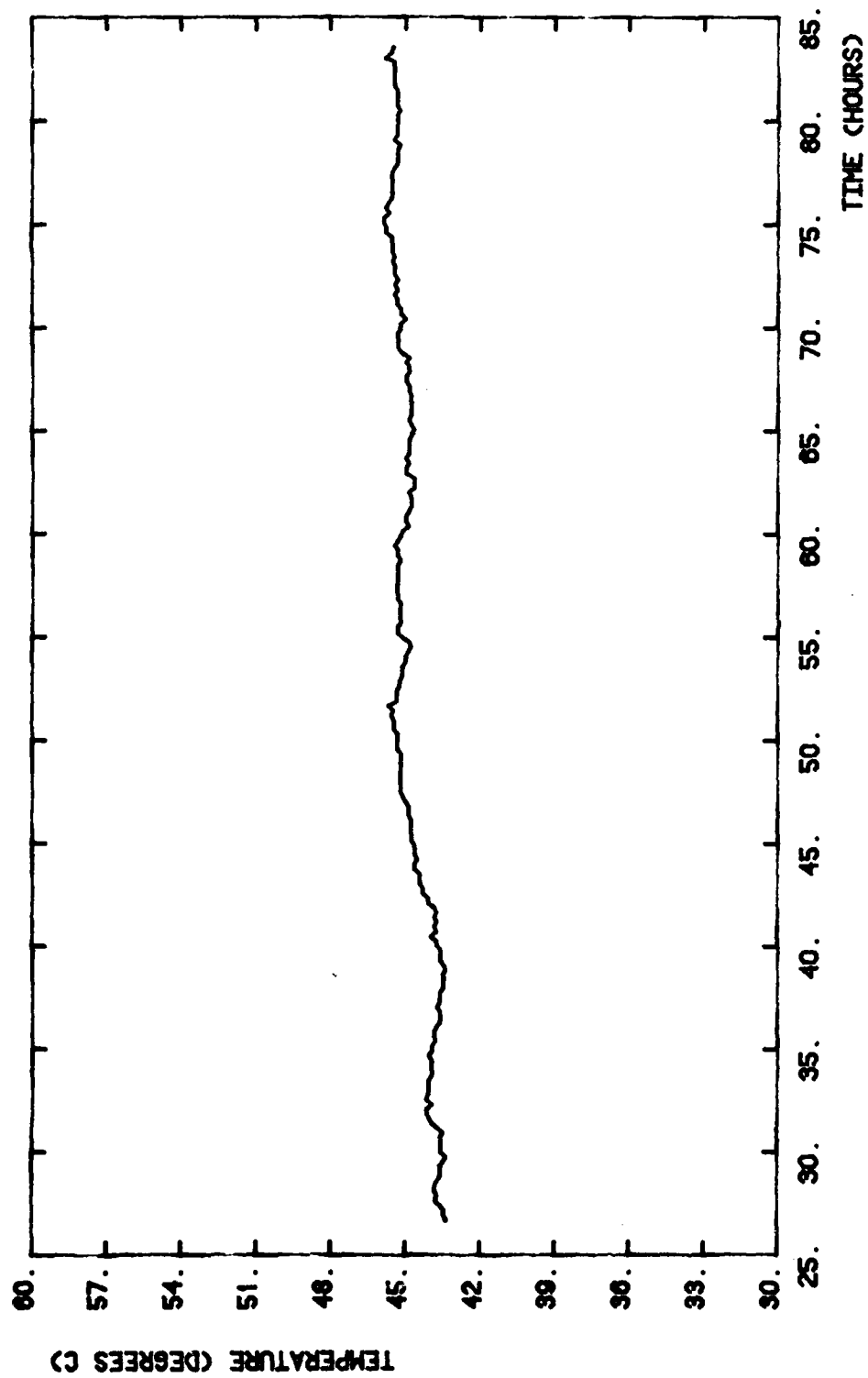


FIGURE 24g

AD-A126 702

THE SALT-GRADIENT SOLAR POND(U) VON KARMAN INST FOR
FLUID DYNAMICS RHODE-SAINT-GENESE (BELGIUM) S T BROWN
FEB 83 EOARD-TR-83-4 AFOSR-82-0201

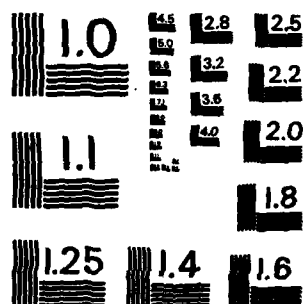
812

UNCLASSIFIED

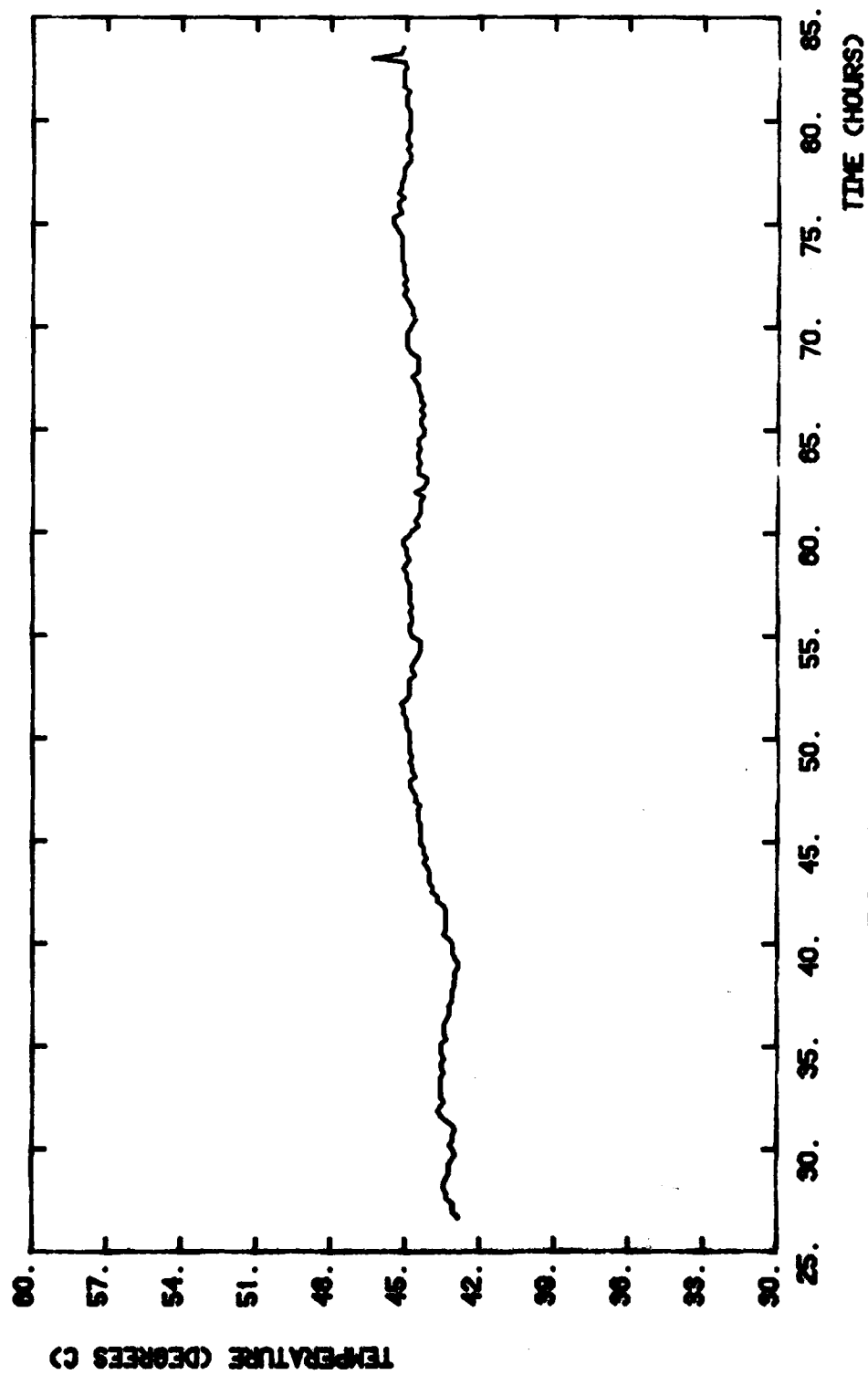
F/G 10/3

NL





MICROCOPY RESOLUTION TEST CHART
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POND80, PROBE 5 (HT.=13.CM)

FIGURE 24h

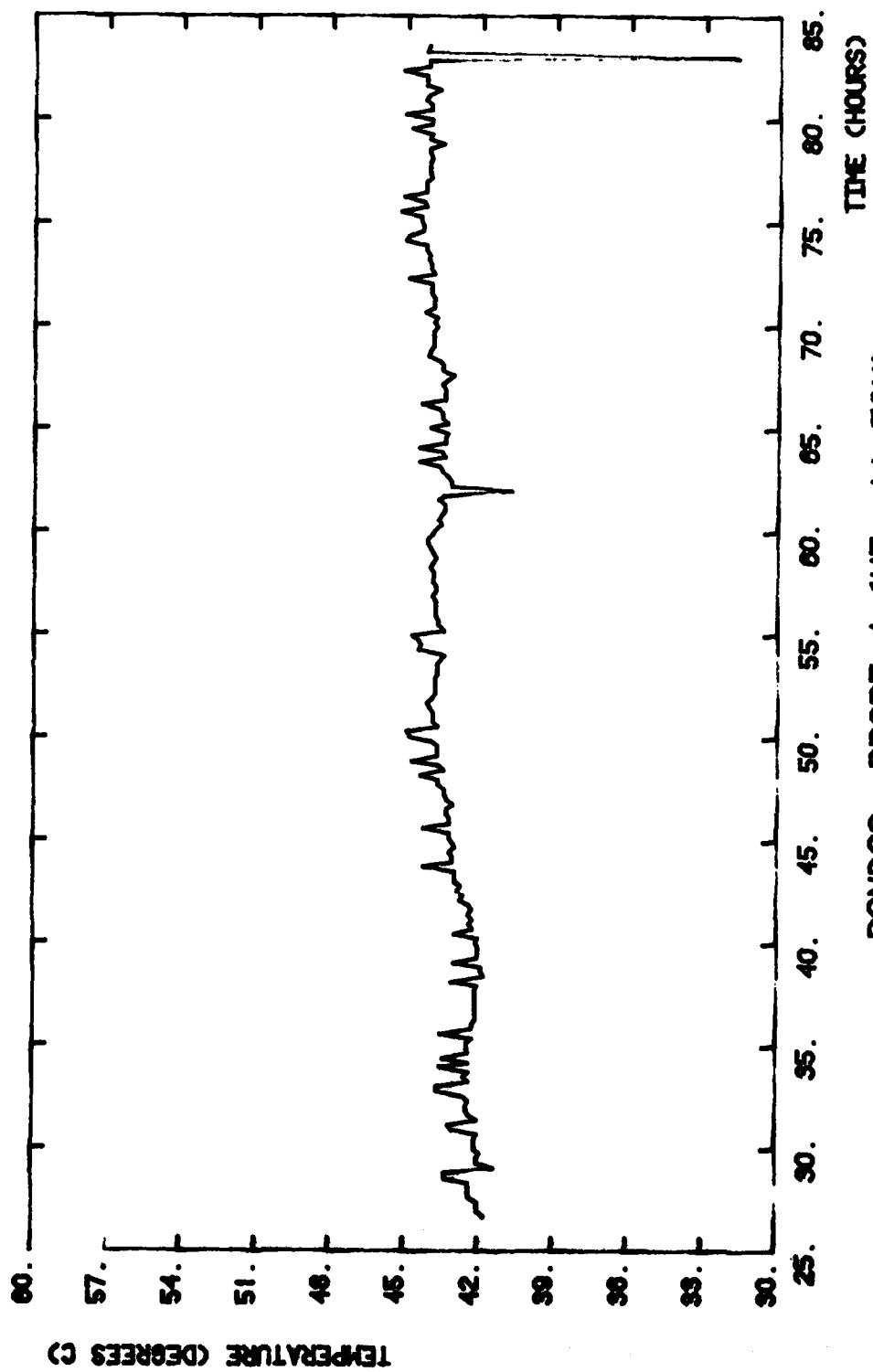


FIGURE 24i

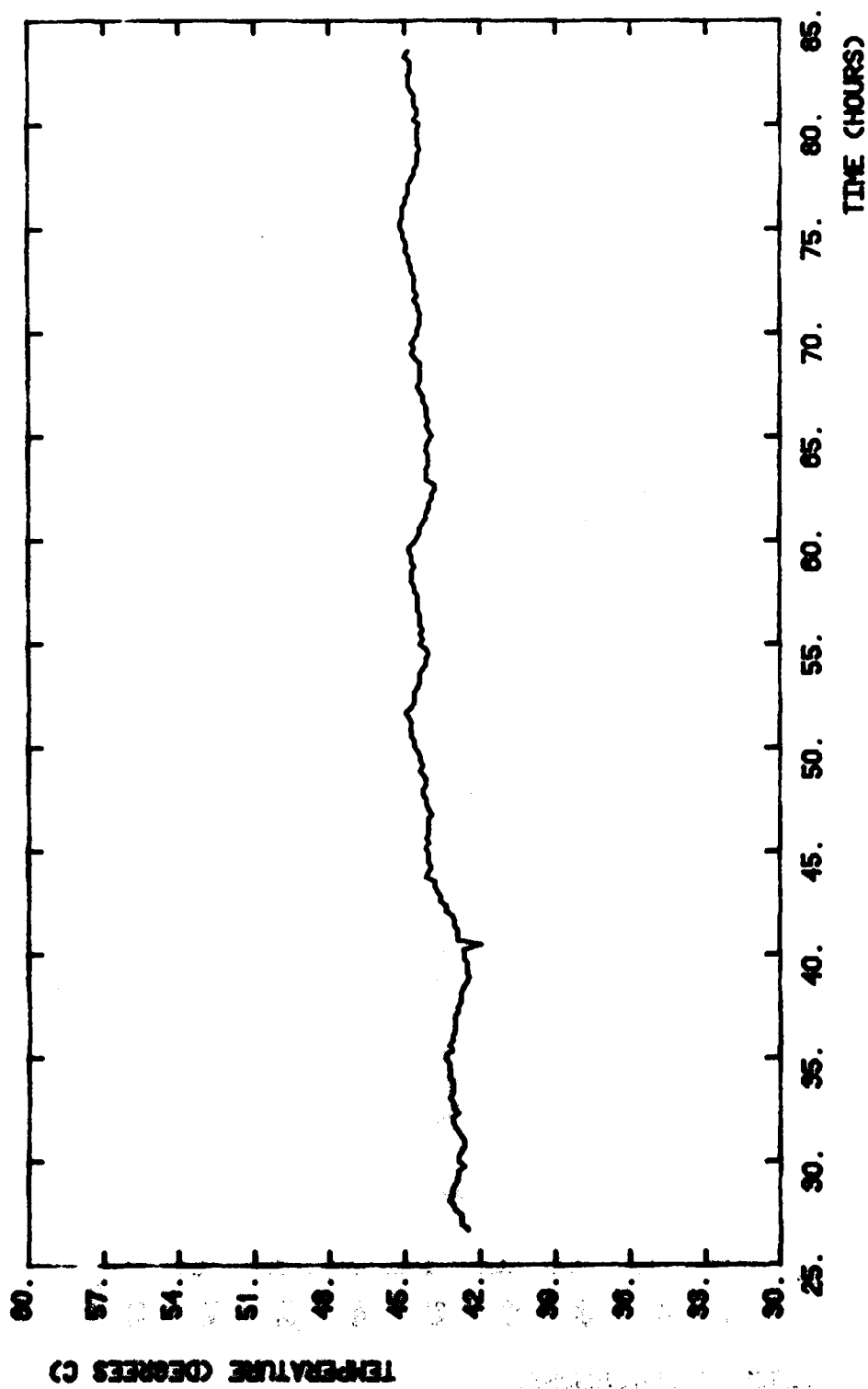


FIGURE 24j

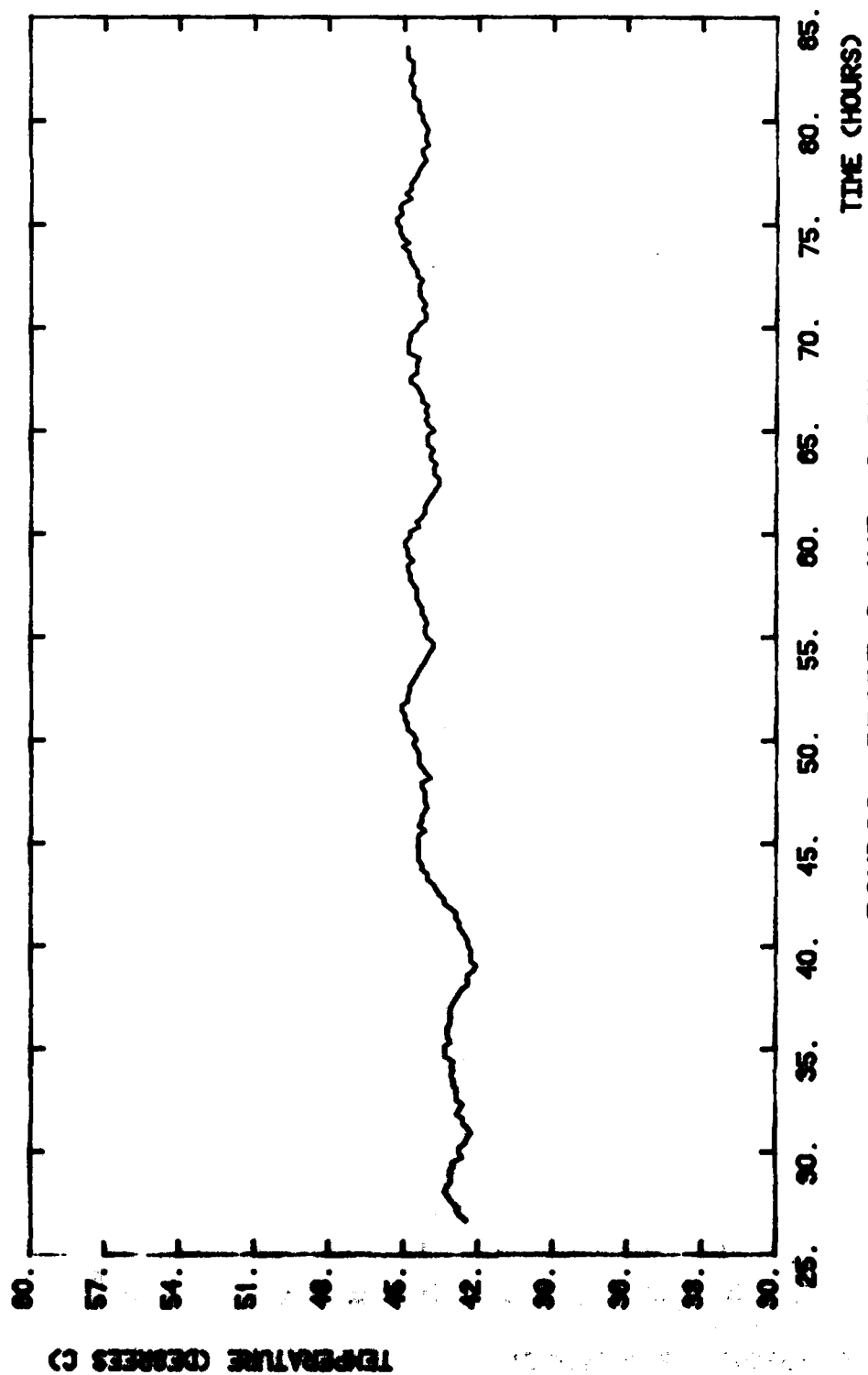


FIGURE 24k

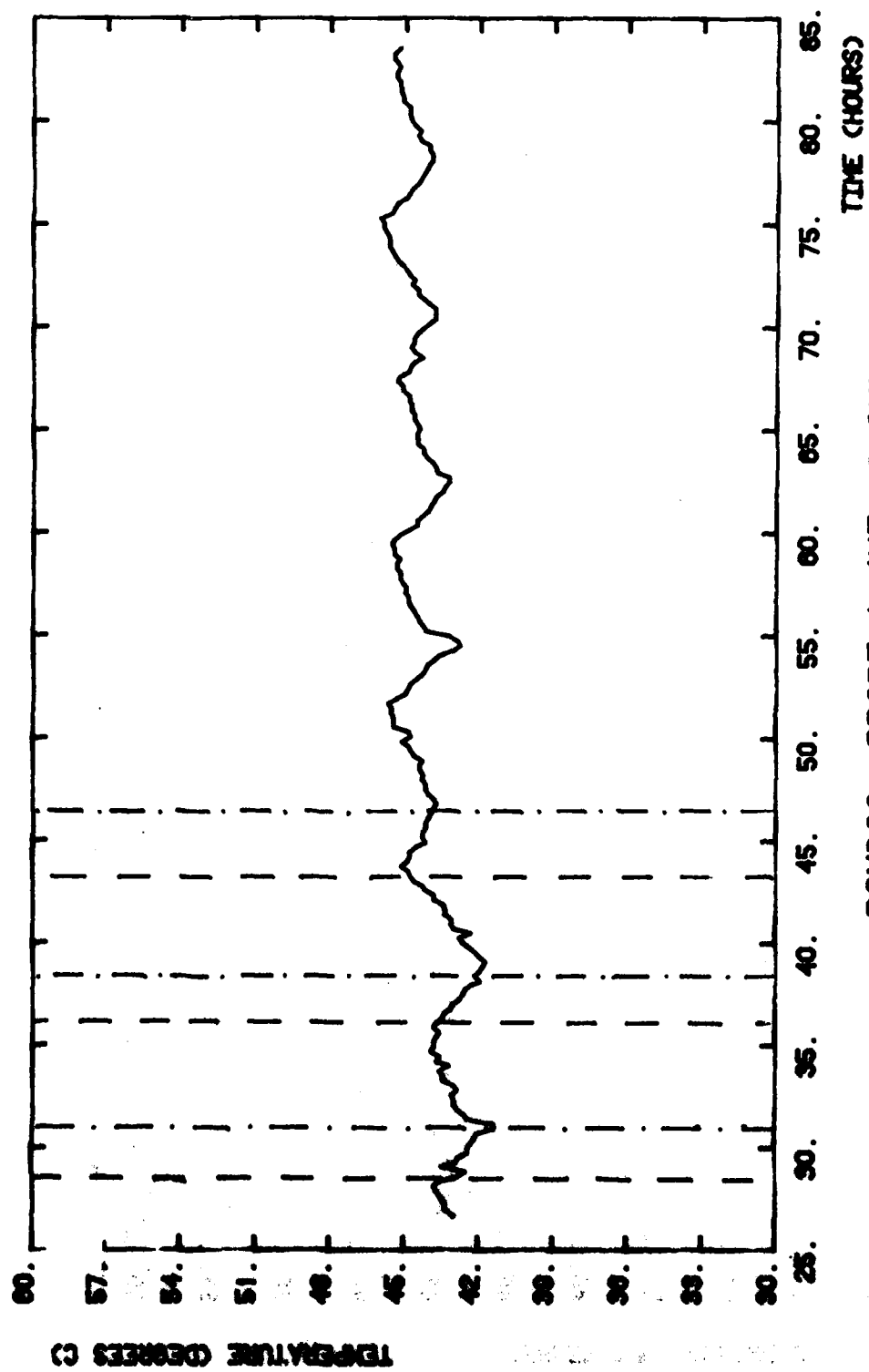


FIGURE 241

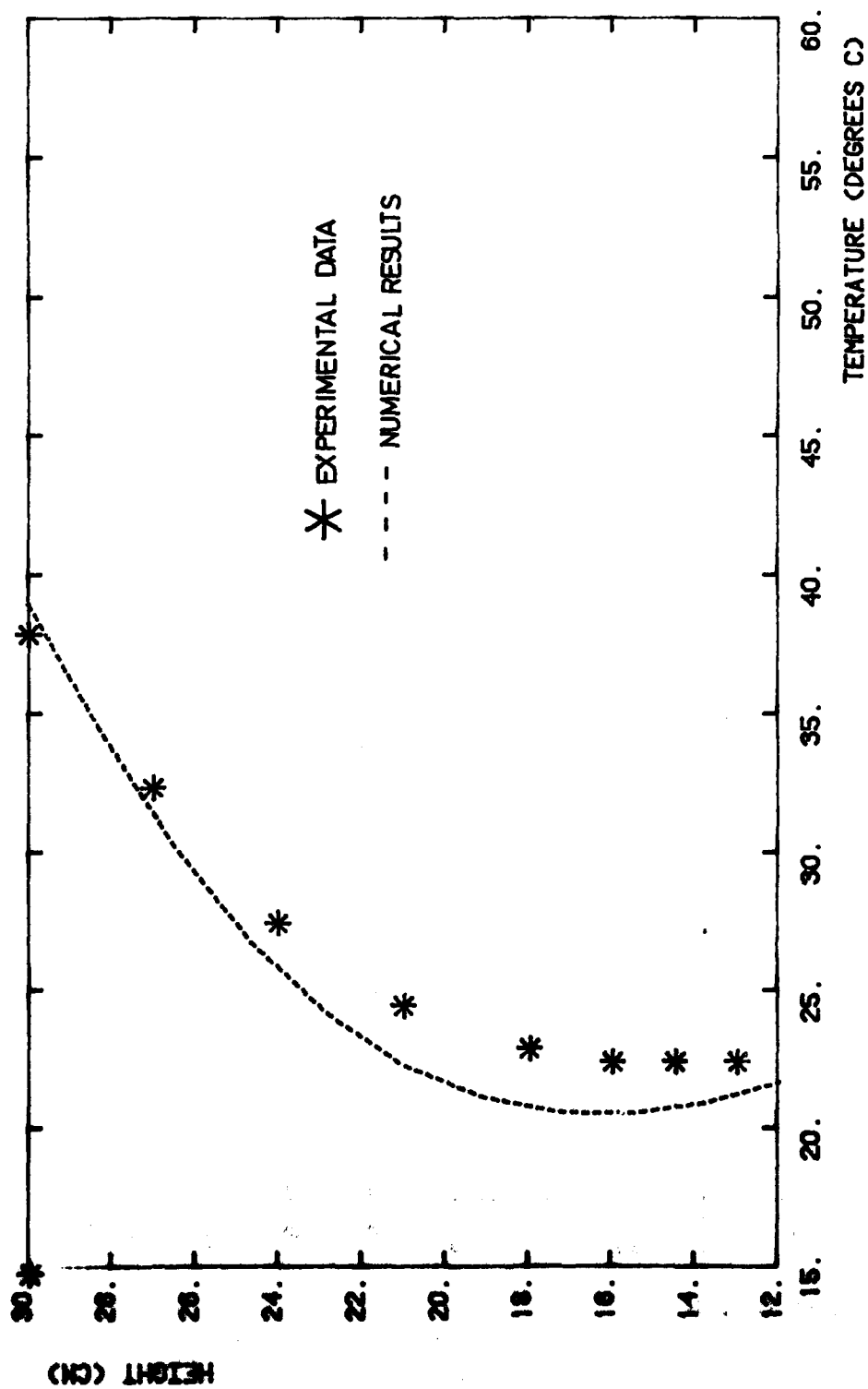


FIGURE 25a

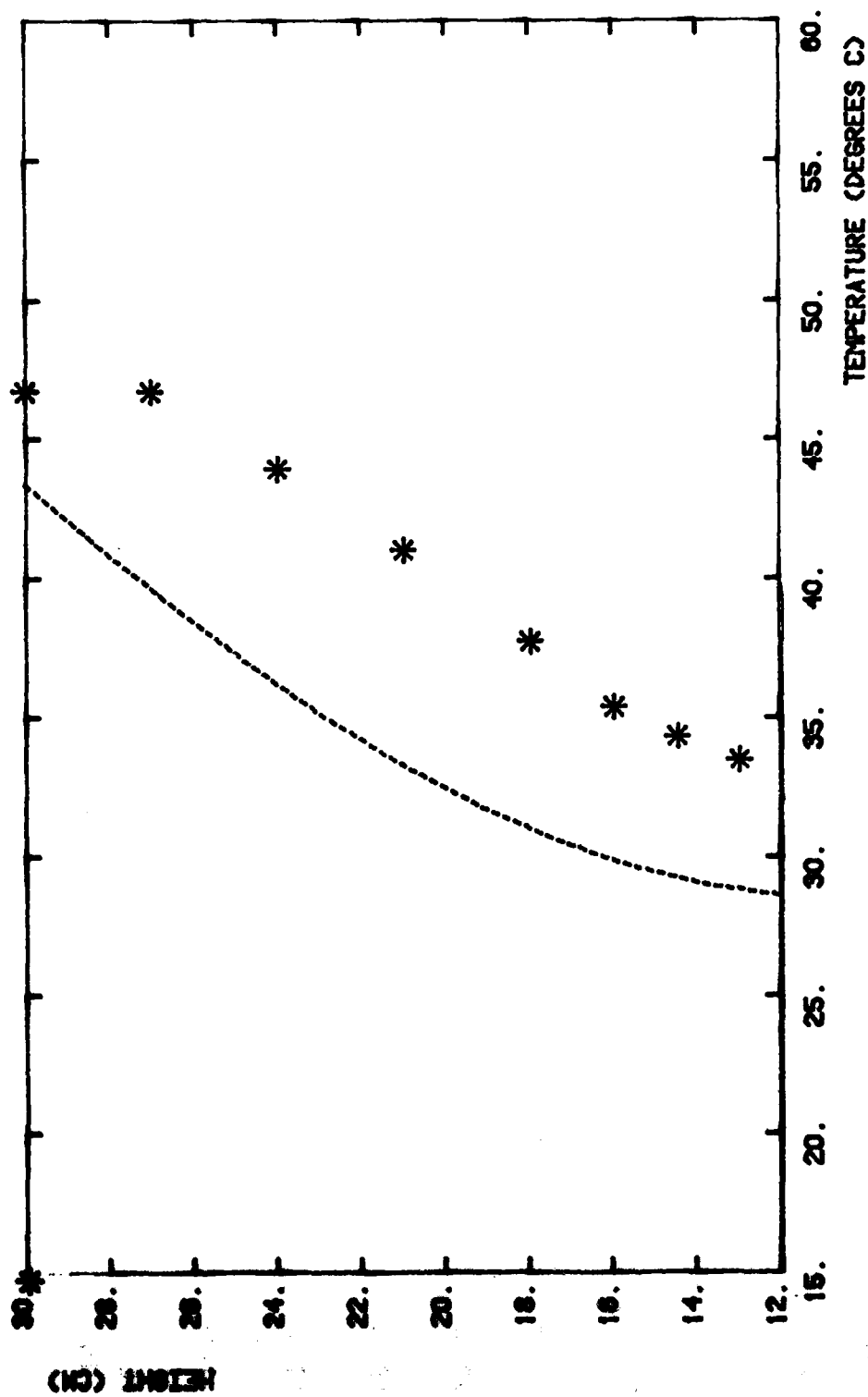


FIGURE 25b

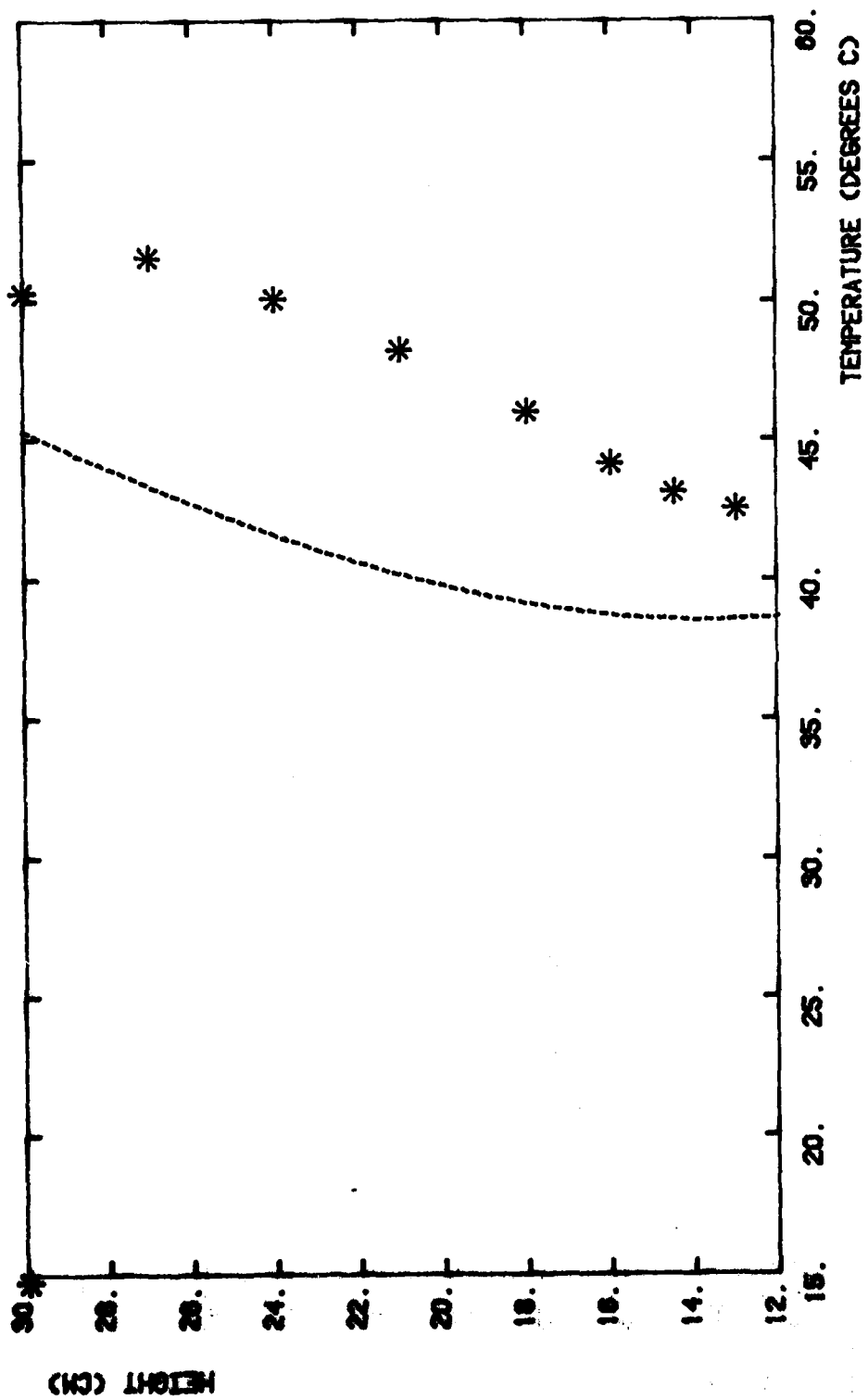


FIGURE 25c

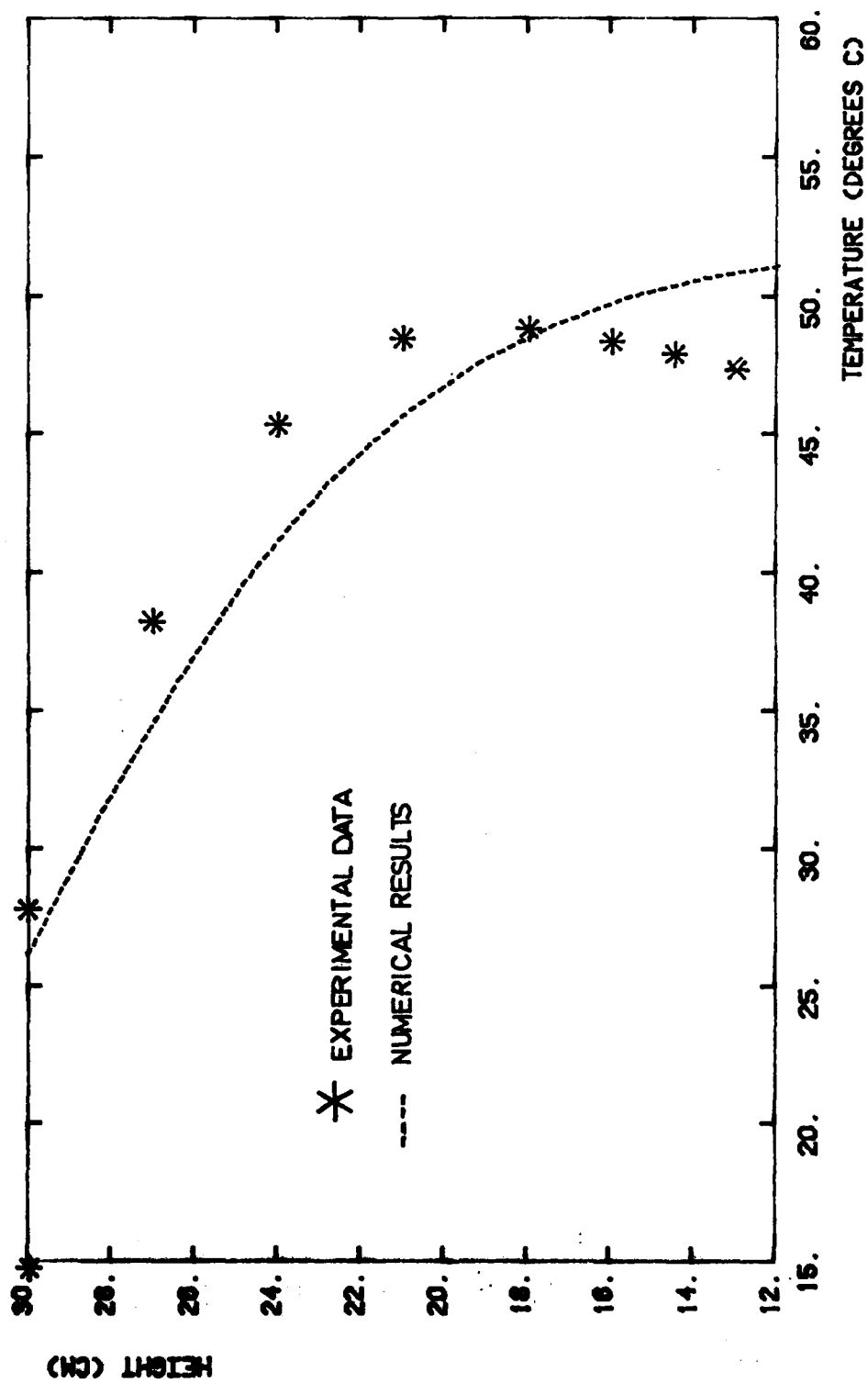


FIGURE 26a

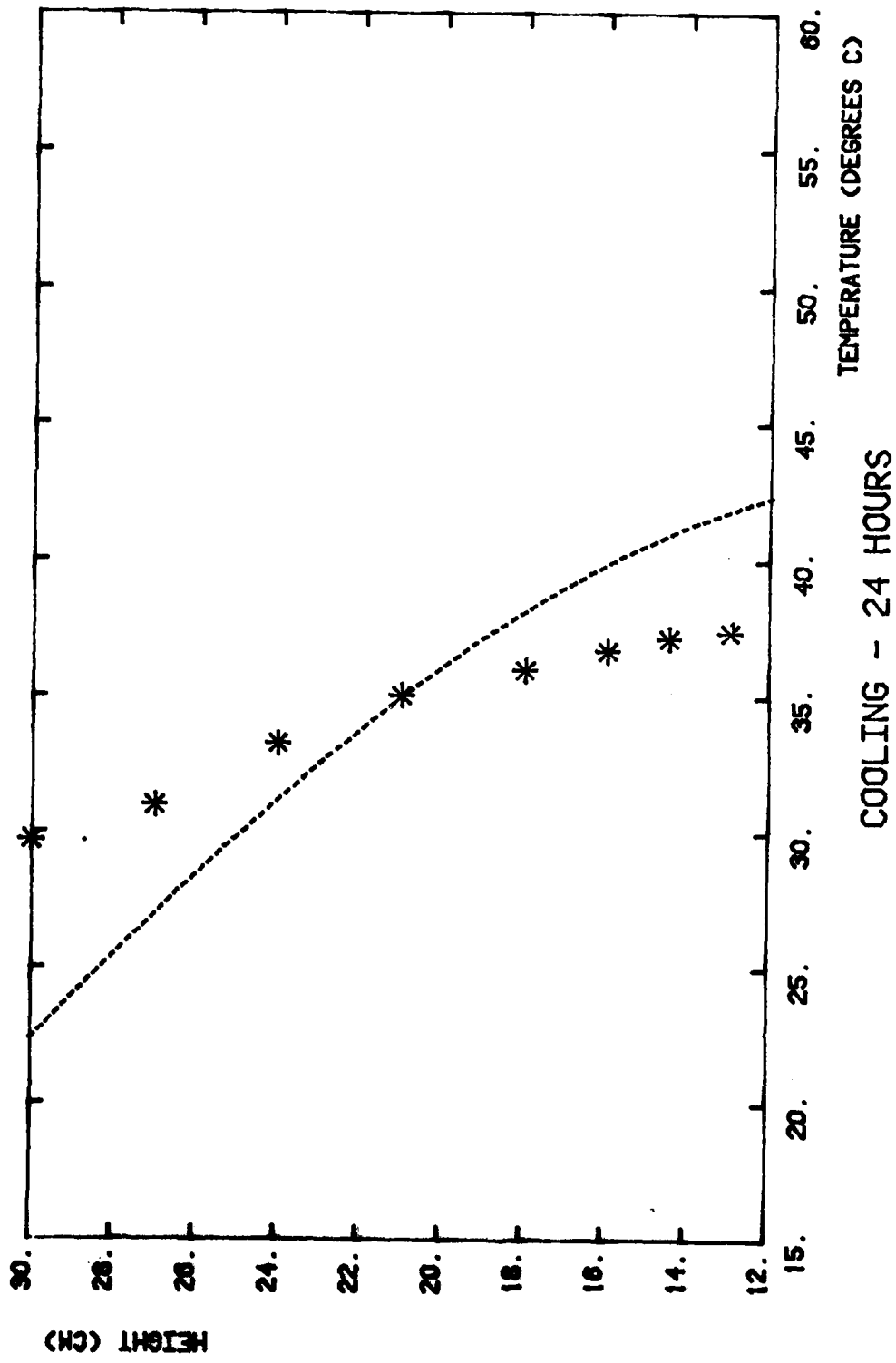


FIGURE 26b

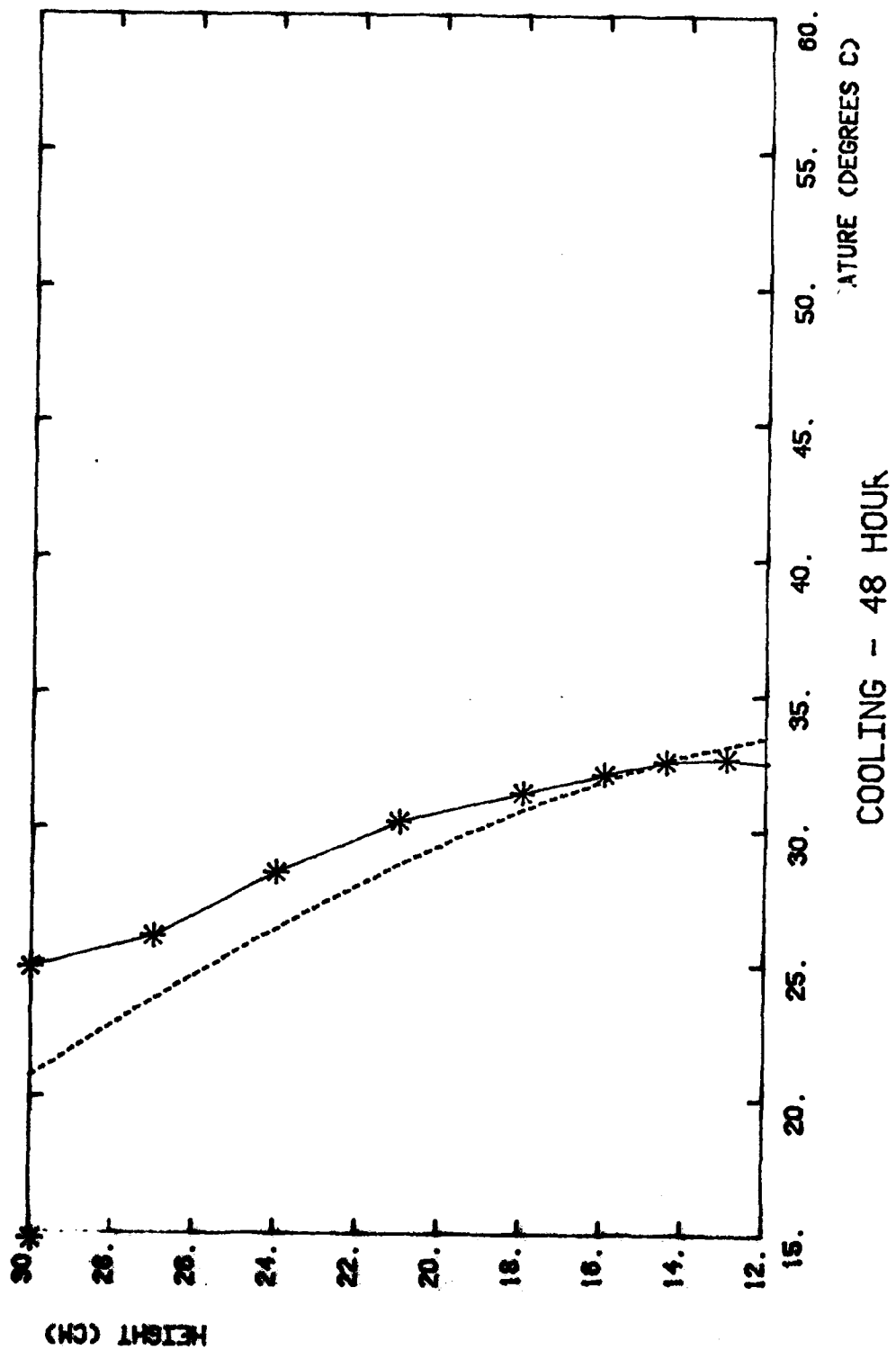


FIGURE 26c

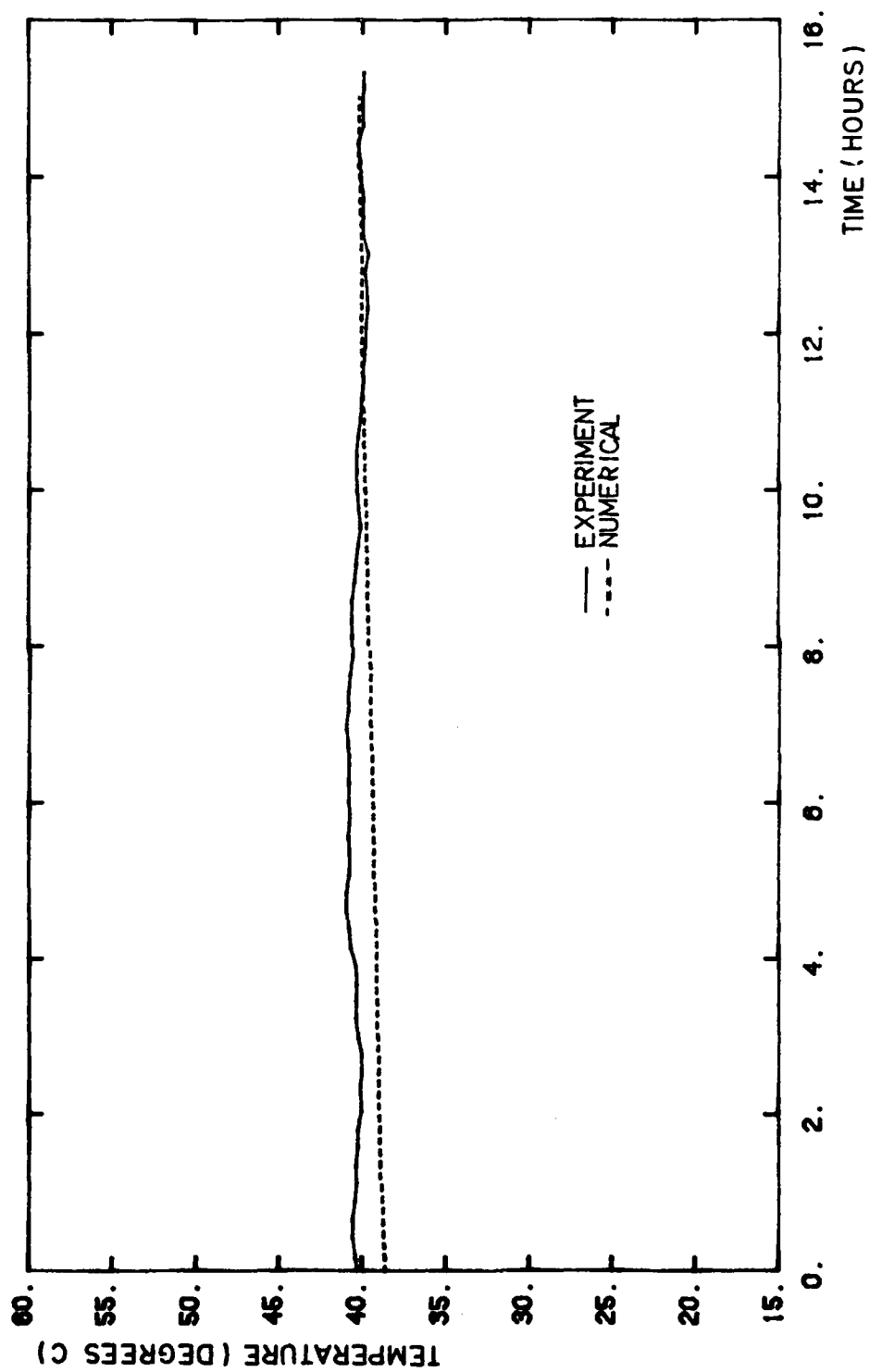


FIGURE 27a

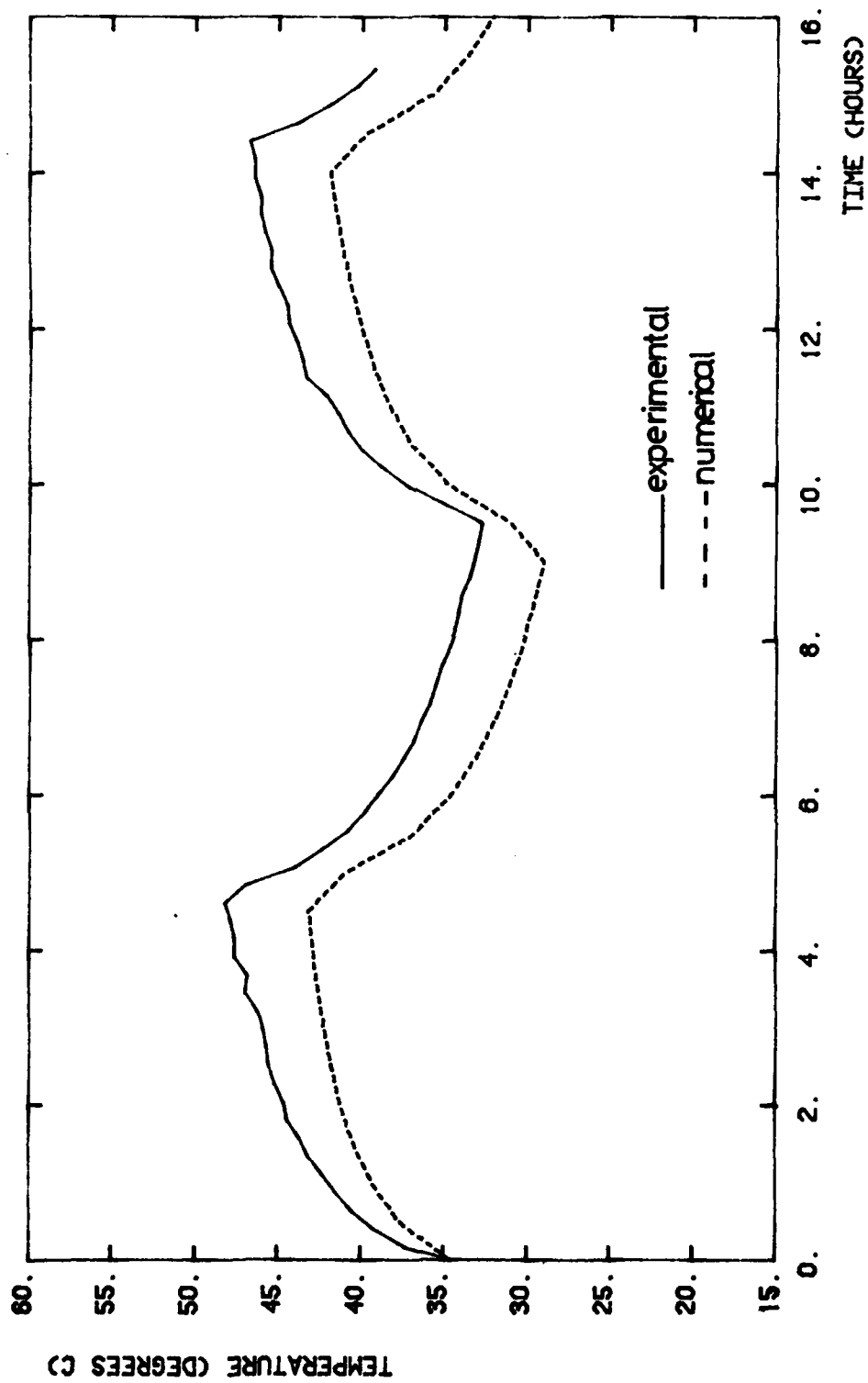


FIGURE 27b

FIGURE 28a
CONCENTRATION PROFILE
during filling of last layer

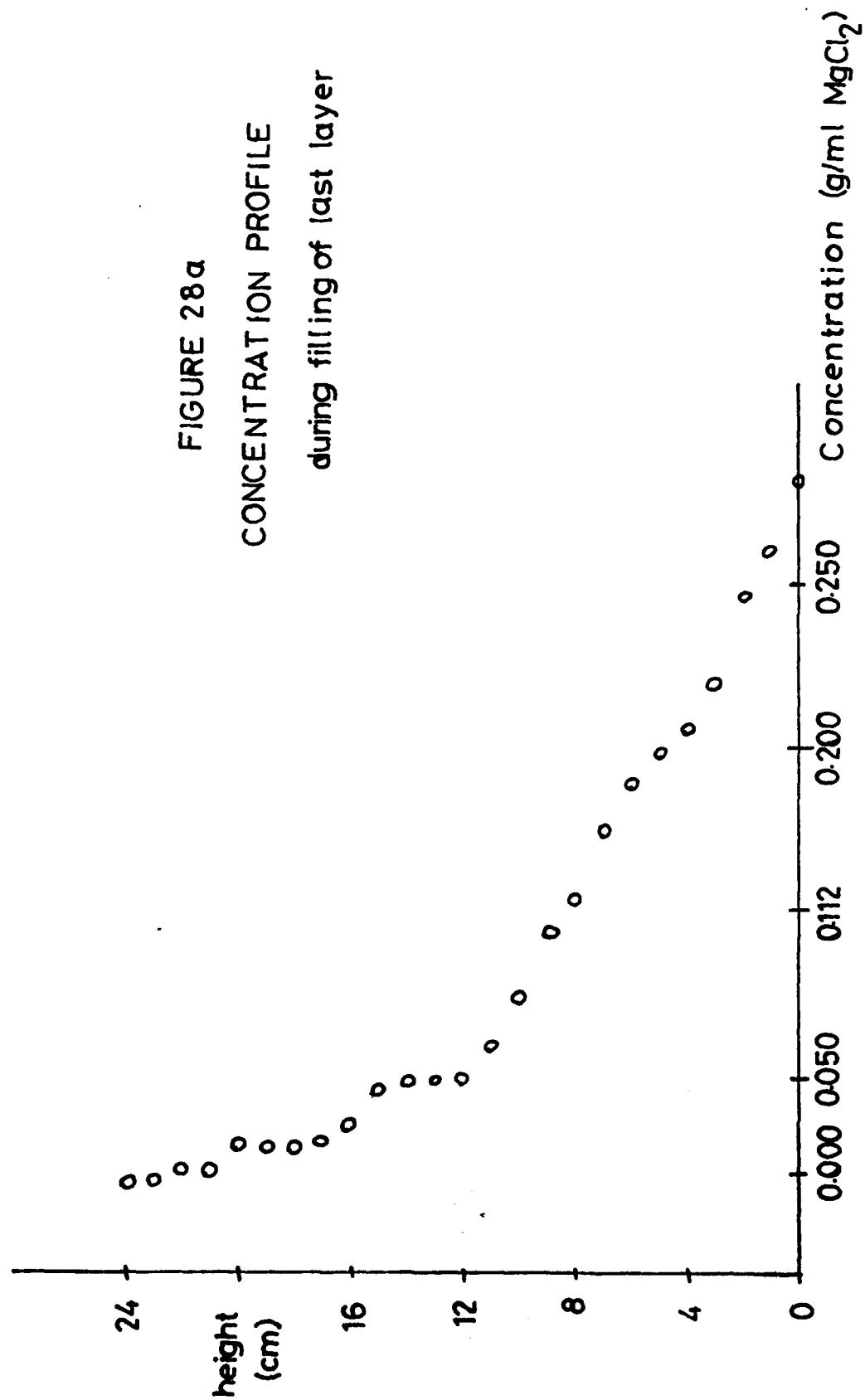
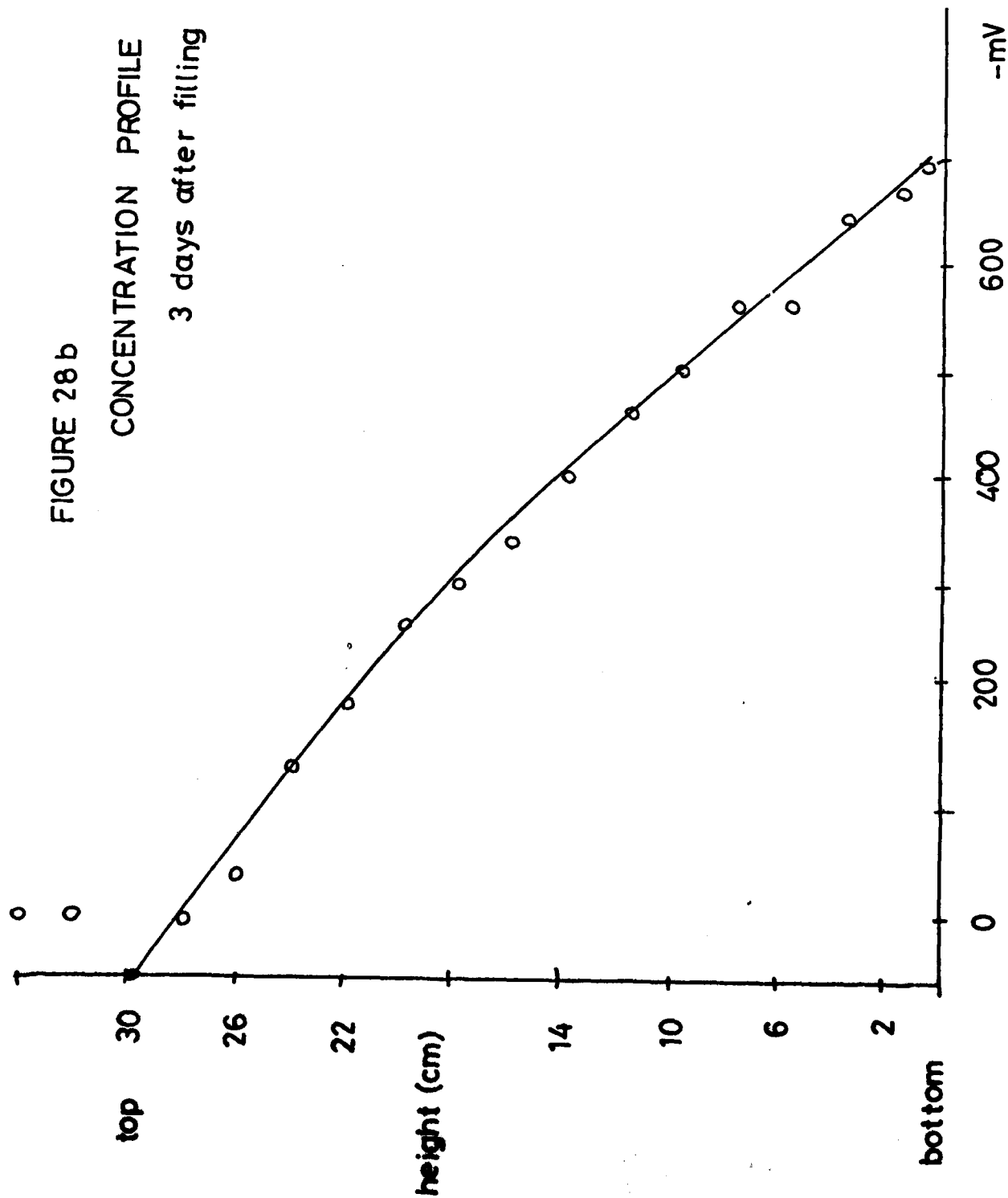
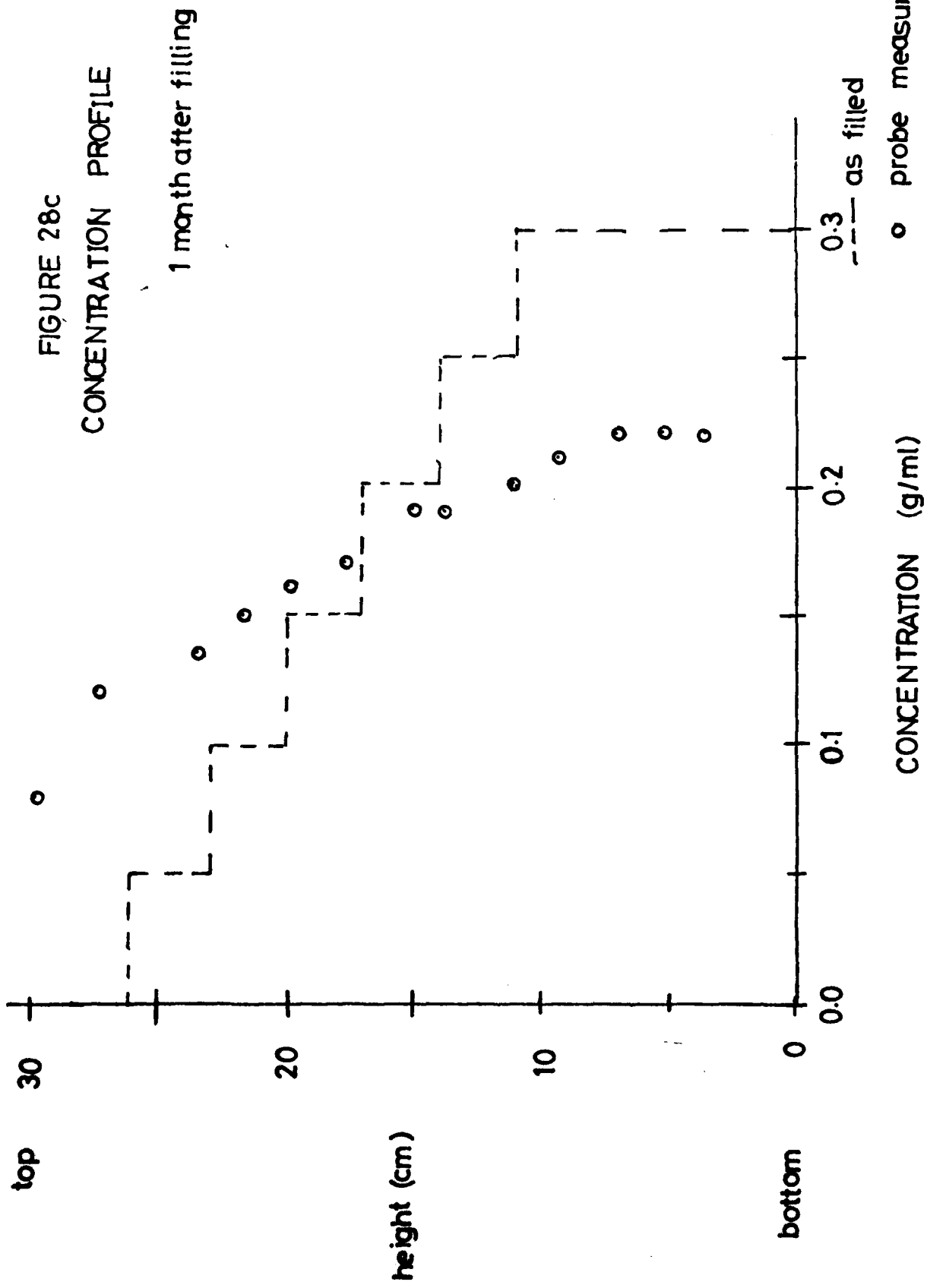


FIGURE 28 b
CONCENTRATION PROFILE
3 days after filling





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