Solar Heating of Wastewater Stabilization Ponds

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Abstract

Performance of wastewater stabilization ponds or sewage treatment lagoons is dependent upon pond water temperature. In recent years there has been considerable interest expressed in raising pond water temperatures in an effort to inprove performance of the treatment process. Solar heat may be one energy source useful in raising pond water temperatures.

In this study the experimental models were designed using a computer model to assess the effect of adding solar heat to waste stabilization ponds. Six model ponds were constructed and sewage water temperatures in both heated an unheated control systems were analysed.

The experimental ponds showed an average temperature increase of 4.7 C (8.5 F) over that of the unheated control pond during the test period using a solar collector effective area equal to pond surface area. Pond surfaces were kept ice-free during the daylight hours. By adding heat at the bottom of the ponds it was possible to increase temperatures and dissolved oxygen levels throughout the depth of the ponds.

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SECTION 1

INTRODUCTION

1.1 General

Waste stabilization ponds were generally not considered for use as a means of wastewater treatment until the 1950's. Isolated incidences of their use occurred prior to the 1950's, in Texas, California, North Dakota, etc., but these were, for the most part, accidental or trial situations. The 1950's and 1960's saw their use begin to take hold. Design criteria, mostly empirical, developed. Today, waste stabilization ponds are considered one of the major types of wastewater treatment systems. They are used extensively by municipalities and industry alike. Their appeal lies in the fact that, economically, they are the best buy on the market today in the area of wastewater treatment systems. They are relatively cheap, simple to operate and place minimum demand on energy resources. Both initial costs and maintenance costs are low and they do not require highly skilled operators. When properly designed, the quality of their effluent is excellent.

Pond performance is dependent upon biological processes. Temperature has been found to be one of the most important variables affecting biological processes. In Southern climates ideal temperatures are possible year round. In climates with cold winters there are some drawbacks to their use, however. Cold weather, ice and snow, can bring the effectiveness of the stabilization pond to a standstill. Design and operation of ponds in cold climates has become such that all or a large portion of winter flows are retained. In view of the rising costs of land, coupled with the push by Federal concerns in recent years for stricter effluent standards, stabilization ponds are becoming less attractive in cold regions.

1.2 Nature of the Problem

Climatic variables, namely temperature, solar radiation, and wind, greatly affect the operation of the waste stabilization pond. Some of the intrinsic effects of these climatic variables on ponds include:(3,10,11,16,18,21)

- variable rates of biological activity
- variable rates of oxygen transfer
- variable degrees of oxygen solubility
- variations in photosynthetic oxygen production
- variations in oxygen and temperature stratification with pond depth

Temperature, in combination with other climatic variables, plays a hand in each of the above effects. Periods of low temperature are especially detrimental to pond performance, being manifest in lower treatment efficiencies and increased detention times. This is shown in Figure 1-1 in a plot of detention time versus percent of BOD removal

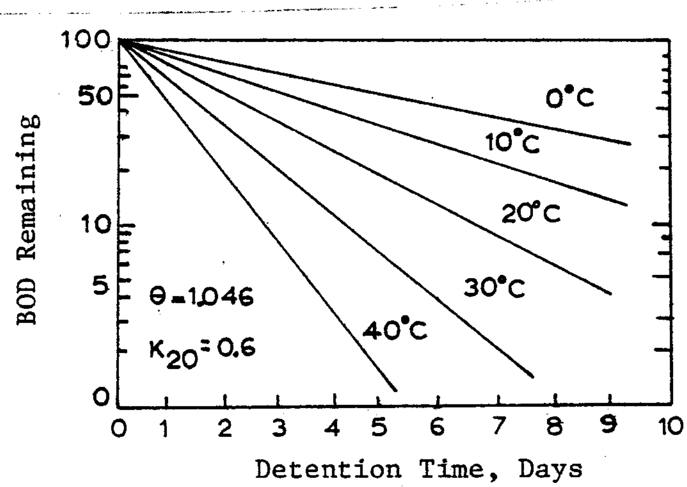

Figure 1-1. Effect of Temperature on Treatment Efficiency

as a function of temperature.[18] The principal reason behind this phenomena is reduced biological activity. In general, the biological reaction rate is said to vary exponentially with temperature.[1,21]

It seems plausible from this discussion that if the temperature of the process could be elevated by a heat input to the pond, then treatment efficiency of the pond could be increased during winter periods. This study proposes to do just that, by applying solar heat to the ponds.

1.3 Study Objectives

The general objective of this study was to investigate the heating of wastewater stabilization ponds, utilizing solar heat in an effort to improve both their cold weather and year-round performance. This paper emphasizes temperature control and heat flow aspects of this objective.

To fulfill this objective a computer model, based on energy balance equations, was developed to predict temperatures of ponds subjected to different solar heating conditions. The model will predict pond temperatures for any month of the year and also for any daily cycle for any day of the year. In addition, the performances of five (5) model ponds, each exposed to a different solar heat condition, were monitored and compared to the performance of a control pond, to the computer model and to each other. Conditions imposed on the ponds in this test enabled comparison of the following:

(1) the effect of pond size on pond temperature for a given size collector,

(2) the significance of utilizing heat storage, and

(3) the consequence of adding heat to a pond by means of a liquid heating collector versus that of a passive system versus no heat addition at all.

The specific objectives of this study were to:

(1) Differentiate the type of solar heating system best suited to improving waste stabilization pond temperature characteristics.

(2) Estimate the size of a pond a given collector system would be capable of heating to a specified temperature.

(3) Determine the effect of heat storage, for overnight use, on pond temperatures.

(4) Determine what effect a transparent pond cover would have on temperature of the pond.

(5) Develop a model that would adequately predict expected monthly pond temperatures throughout the year and also predict daily cyclic pond temperatures for any given day of the year.

(6) Verify the model predictions with actual pond performance.

SECTION 2

LITERATURE REVIEW

2.1 General

A stabilization pond (or lagoon) is defined as a relatively shallow body of water contained in an earthen basin for the purpose of treating wastewater.[30] The term "stabilization pond" is a very general term. Broadly used, it can refer to several types of ponds. These include: anaerobic pretreatment units, faculative ponds, high rate aerobic lagoons, maturation ponds, mechanically assisted ponds, aerated lagoons, etc.[21] Faculative ponds are by far the most widely used type of stabilization pond in the world today and are the type of pond used in this study. Therefore, to avoid confusion, the term "stabilization pond," when used within the context of this paper, will refer to the faculative type pond.

2.2 Nature of Stabilization Ponds

Organic waste entering a stabilization pond separates into two portions. A sludge portion, which settles on the bottom of the pond, and a liquid portion containing soluble organic compounds.[11,21] Bacteria present in the pond are the primary organisms responsible for the degradation process. Bacteria breakdown complex waste products into simple organic compounds that they use or modify and release back to the pond environment.

In the sludge and lower layers of the pond the bacteria performing this function are predominantly anaerobic. That is, they function in a habitat devoid of oxygen, releasing gaseous products, methane, carbon dioxide, nitrogen, etc., which rise and escape to the atmosphere. They also release soluble organic products that become mixed into the liquid portion, thereby raising the BOD of the liquid portion.

In the liquid portion, soluble organic compounds are degraded through the actions of aerobic and faculative bacteria. Oxygen support to these bacteria is provided, primarily, through algal photosynthesis, mixing and, to a limited extent, through surface gas transfer. The bacteria in turn, replenish, through oxidation of organic matter, the carbon dioxide algae required as a carbon source for biomass production during the photosynthetic process. This cyclic symbiotic relationship between bacteria and algae is the key behind the efficient functioning of the waste stabilization pond. It is, therefore, theoretically recommended that waste stabilization pond design be based on the concept of maximum algal production.[8]

2.3 Environmental Factors

Performance of the stabilization process is primarily dependent upon the extent of microbial activity present within the pond. The microbes of primary importance in this process are bacteria and algae. The extent of microbial activity, in turn, is dictated by a number of physical and chemical parameters. This discussion will focus on the physical aspects. Three of the major physical parameters affecting pond performance are temperature, solar radiation, and mixing. These parameters are dependent upon climactic conditions, making ponds essentially an uncontrolled process.

The rate at which biological processes occur within the pond liquid and sludge layer are highly temperature dependent. Temperature affects the rate of enzyme catalyzed biochemical reactions. The biological reaction rate constant, K_T, varies with temperature according to the modified Arrhenius equation.

$$K_T = K_{20}\ \theta^{(T-20)}$$

where:

K_T = rate constant at some temperature, T

K_{20} = rate constant at 20°C

T = desired temperature, °C

θ = temperature coefficient, reported values used range from 0.985 to 1.145[26]

A plot of a typical reaction rate versus temperature is shown below.[18]

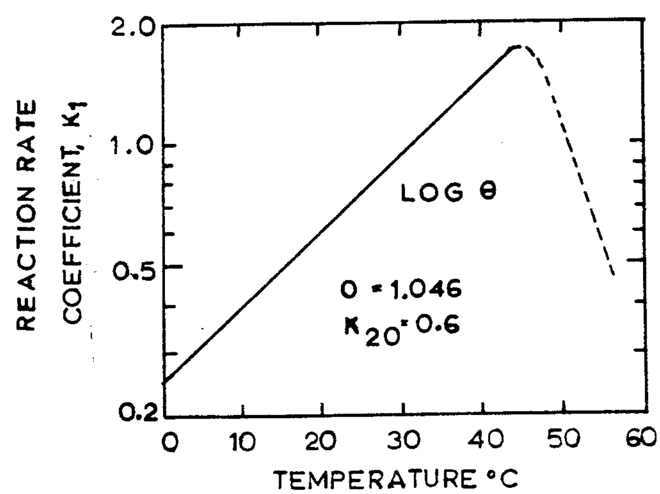

Figure 2-1. Effect of Temperature on Reaction Rates

Note, at low temperatures bacterial activity is greatly retarded. Algal activity is also retarded at low temperatures. Even under conditions of high solar radiation, intensity of algal growth is affected by low temperatures.[21] The useful temperature range for the pond is from 41°F to 95°F (5°C to 35°C). The optimum range being between 77°F and 95°F (25°C and 35°C).[10,14]

Algal activity varies with sunlight, climate, and in turn, geography. Temperature and sunlight become greatly reduced in Northern winter climates. When ice and snow cover the stabilization pond during the winter months, sunlight is reduced to the point where algal photosynthesis becomes ineffective, thus negating the principal means of pond reoxygenation. Also prevented is the physical reaeration of the pond by gaseous diffusion of oxygen at the water surface. During such winter conditions the aerobic processes become virtually ineffective. In addition, anaerobic processes lose their effectiveness at approximately 59°F (15°C).[10] Therefore, during winter periods biological activity is minimal, there is very little BOD reduction, and sludge accumulation occurs. As temperatures rise in the spring biological activity increases. The sludge layer begins to digest anaerobically at a very high rate, resulting in a pH drop, an increase in hydrogen sulfide production and odor release from the septic wastewater.[3]

Temperature and oxygen stratification inhibit pond performance by maintaining separate aerobic and anaerobic zones. Stratification, which is worse during winter months, results from a lack of mixing of pond contents due to temperature caused density differences throughout the pond depth. There are two mixing mechanisms: wind and thermal mixing.[21] Wind mixing is the more effective of the two in ponds as we know them today. Without mixing, the pond remains stratified, confining the aerobic layer to the top. Mixing redistributes the oxygen and nonmotile algae throughout a greater pond depth resulting in more effective use of the pond.[16,21] Good mixing increases pond capacity. In addition, the aerobic layer is said to serve as a deodorizing seal, promoting oxidation of rising anaerobic products.[3,16] Therefore, the greater the aerobic depth, the less offensive the lagoon.

Addition of solar heat to a pond may aid pond performance and acceptability by reducing the impact of two pond problems brought out in the above discussion; stratification and offensive odors. Stratification problems may be reduced and pond capacity increased if the heat were introduced at the pond bottom, thereby destroying the temperature gradient from top to bottom and allowing more pond mixing. Offensive odors may also be reduced with increased mixing and a greater amount of biological activity during the colder periods.

2.4 Solar Energy

Electromagnetic energy (solar radiation) originating on the sun from thermonuclear reactions travels through space and penetrates the earth's atmosphere. This phenomena is fundamental to man's existence here on earth. During the past several years man has been attempting to make more use of this resource through collection of the sun's energy for his own energy needs.

To determine how much heat energy can be captured by a solar collector it is first necessary to determine how much solar energy falls on a tilted surface located at the point in question here on earth. The amount of solar radiation present at a point in space varies with distance from the sun. Because the earth's orbit is elliptical about the sun, this distance varies about 3% throughout a year.[7,28] At the mean distance from the sun the amount of solar radiation is essentially constant and termed the solar constant. The amount of solar radiation reaching the outer reaches of the earth's atmosphere on a horizontal surface may be calculated as a function of the solar constant, latitude, and time of year. The amount of radiation making it through to the earth's surface is reduced from this extraterrestrial value by a number of climatic and environmental factors such as cloud cover and pollution.

To maximize solar energy collection the solar collector is tilted perpendicular to the sun's rays. To do so continuously would require elaborate tracking collectors. For a fixed position flat plate collector, however, maximum energy collection in the Northern Hemisphere is gained during the heating season when the plane of the collector is tilted from the horizontal at an angle of the latitude plus 15^o.[28] The collectors used in this study were tilted 55^o to the horizontal. Preferred collector orientation is due south, making the sun's daily track symmetrical relative to the collector.

Most solar radiation data available today are average values for horizontal surfaces. To derive the amount of useful heat captured by a solar collector this value must be converted to values incident on a tilted surface. Liu and Jordan present one method for calculating a radiation conversion factor, R.[28] Average daily radiation on a tilted surface becomes:

$$\bar{H}_T = \bar{R}\,\bar{H}$$

where:

$\bar{H}_T$ = average radiation on a tilted surface,

$\bar{R}$ = fraction of average daily radiation on a tilted surface compared with a horizontal surface,

$\bar{H}$ = average radiation on a horizontal surface.

Values for $\bar{H}$ are available from local data or from national solar radiation maps. Values for $\bar{R}$ may be calculated for a particular site from available data or found in the literature.[7,17,28,29]

2.5 Related Studies

The use of solar heat in an attempt to improve the cold weather operation of waste stabilization ponds has not been extensively studied to date. No other studies were found utilizing this particular method. Related studies, employing various other methods for heating ponds, are available, however.[2,14,15,19,20,24,35] Because the heating methods are different from that of the solar heated ponds conclusions derived are not directly comparable. The studies are significant, however, because of the basic similarity in their concepts.

The combined utility concept, using stabilization ponds as a positive method for dissipating power plant waste heat through closed loop heat exchangers, has been widely proposed.[2,14,15,29,35] Oswald endorsed this concept, citing potential increases in waste decomposition rates found in such ponds exceeding by 100 times those found in nature, as an incentive for further investigation of this alternative.[24] In addition, he reports the rate of anaerobic fermentation increasing 30 times between temperatures of 59°F and 80°F (15°C and 30°C) and algal growth persisting in the winter at temperatures greater than 59°F (15°C) as further motivating factors for pursuit of this idea.

Incropera investigated the potential of using waste heat from power plants as the energy source for wastewater treatment and algal production.[14] Mathematical models, similar to the ones used in this study, were used to evaluate the heat transfer properties of the pond/heat exchanger system. The performance response of the pond system to heat inputs was evaluated using a complex mix activated sludge model. Results of the study show that from a standpoint of total effluent quality, it is desirable to operate at elevated temperatures, that effluent quality improves for any increase in temperature from 50°F to 86°F (10°C to 30°C) and that it is possible to maintain optimum temperatures year round in the Midwest using this heat source.

The use of geothermal well water as the heat source to improve aquaculture productivity of the organism *Macrobrachium rosenbergii*, shrimp, in temperate zones such as the United States, was investigated by Klemetson.(19) A computer model, using heat balance conditions similar to this study was used to predict pond temperature and productivities of the organism at well sites in Southern Colorado. Maximum productivity of the organism was found to occur at 82°F (28°C), decreasing to a minimum at 62°F (17°C). Input temperatures were taken as 87°F (31°C). The results yield pond sizes too small to be practical for year-round use. Enclosing the ponds yielded larger areas, but this method was considered inapplicable to large areas from a cost standpoint.

Waste power heat and geothermal well systems are not directly comparable to the solar heated waste stabilization ponds of this study from the standpoint of heat source. The geothermal wells and waste power heat are both continuous constant temperature sources. Solar heat supply varies directly with the climatic conditions and time of day. In addition, the organisms involved in the well study are different from sewage organisms to the extent of being almost incomparable. Life and growth cycles are different, as are the temperatures at which they operate, the stabilization pond organisms being much more durable at all temperatures.

A lagoon system with a transparent cover was studied by Laak in Connecticut to determine the feasibility of covered lagoon systems for use as a wastewater treatment alternative.(20) Preliminary results reported the system feasible. Operational parameters are similar to that of a normal faculative/anaerobic lagoon system and no odor problems were reported. Additional study is being conducted to evaluate the effect of long-term seasonal stresses, effect of sludge age and accumulation. The results of covered lagoons in the present Colorado study are similar to these. The Colorado lagoon is highly stratified, as most likely is the Connecticut lagoon, and it is doubtful that much sludge digestion occurs in either.

At present, research in the area of stabilization pond heating is still in the infant stages. It was not until recent years (past decade or so) that the idea was even seriously considered. As such, pilot studies in this area are limited. Much understanding about the construction, design and workings of the system is to be gained from such studies. Because of this, this study will include pilot studies.

SECTION 3

EXPERIMENTAL METHODS

3.1 General

The experimental approach for this study utilized construction of six model pond systems. Each pond was dug into the earth, lined, filled with wastewater to seed the pond, and fed at periodic intervals with a synthetic waste. Solar heat was added to five of the ponds through one of the five collection schemes designed to execute the objectives of this study. The sixth pond was used as an unheated control. The ponds were monitored continuously for temperature. Dissolved oxygen and temperature profiles of the ponds were monitored routinely. In addition, BOD_5 samples were taken on a regular basis to estimate effectiveness of the added heat to the pond.

3.2 Test Site Location

The test site for this study was located on the eastern slope of the Rocky Mountains, just west of the City of Fort Collins, Colorado near the Colorado State University Engineering Research Center on roughly a 20,000 square foot plot of land. The latitutde and longitude were 40°55'N, 105°8'W, respectively.[6]

Climatologically, the site area is characterized by mild temperatures, light winds with occasional strong chinooks and light precipitation. Temperatures vary from a monthly average of 27.5°F (-4.5°C) in January to 71.4°F (18.6°C) in July. Annual precipitation averages about 15 inches, and snowfall about 46 inches.[6] Extended snow cover is unusual.

This site was chosen for the following reasona:

Open area. No obstructions interferring with solar radiation.

Flat area. Facilitates easier construction.

Access. Easy access via pickup truck to aid in system construction and maintenance.

Power. Nearby source of power for construction tools, pumps, thermostats, recorder, etc.

Water. Nearby source of water for synthetic waste mix used to replenish lagoons, heat storage water, cleaning, etc.

Meteorological data. Source for precise measurement of weather data, solar radiation, etc. Located within a few hundred feet at CSU Meteorological Station.

3.3 Model Ponds

The site layout of the six model systems is shown in the schematic of Figure 3-1. A photograph of the actual layout is shown in Figure 3-2a. Three different pond sizes were used in this study. Variation in pond size was with respect to surface area (surface area being the primary geometric variable controlling pond heat losses). All ponds had a 3.5 foot water depth with six inches of freeboard. Pond surface areas used were 11, 16, and 24 square feet. The operating volume of these ponds were 290, 420, and 630 gallons, respectively.

The 16 square foot pond surface area served as a control size, enabling comparison between different types of solar heated pond systems. This standard pond size was decided upon following preliminary calculations using an energy balance model for a pond with solar heat added through a thermal exchanger (no heat storage). This energy balance used monthly average temperatures typical for the months of

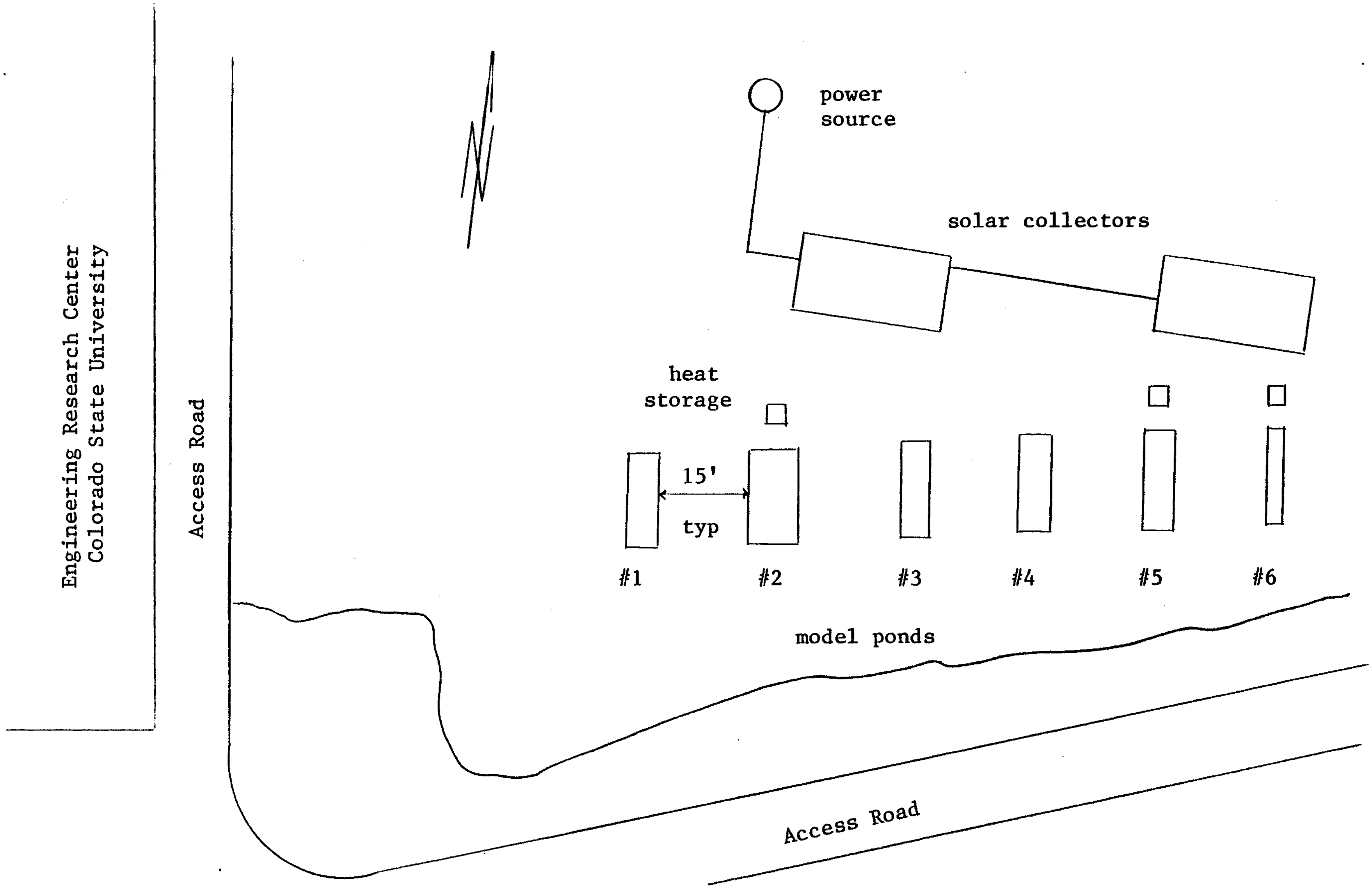

Figure 3-1. Schematic Of Site Layout.

Figure 3-2a. Site Layout

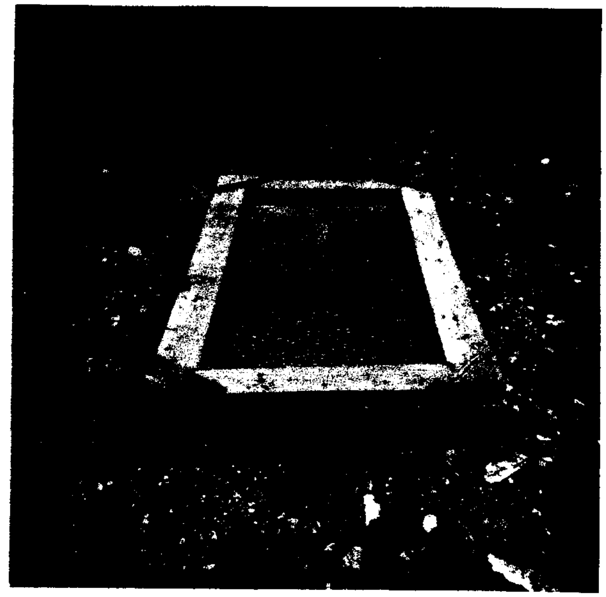

Figure 3-2b. Lagoon with Transparent Cover

Figure 3-2c. Flat Plate Collectors

Figure 3-2d. Lagoon Thermal Exchanger

Figure 3-2. Model Ponds

November and March, taking into consideration minimum and maximum temperatures, night and day. Prelminary calculations had shown it impractical to size the ponds for colder months, as unfrozen pond area becomes impractically small compared to collector size. A more detailed account of the energy balance model and pond sizing is given in the next section.

A schematic showing typical pond construction is shown in Figure 3-3. Individual ponds were excavated with a backhoe. Ponds were framed with 3/4" plywood, lined with two courses of polyethylene (6 mils thick) and backfilled. The 3/4" plywood frame was used to prevent sidewall cave-ins and to yield a more precise pond surface area. The liner prevented seepage. Pond overflow was through an 8" wide metal trough.

The six model pond systems operated in this study are summarized as follows:

(1) Control pond, standard size, no solar heat added.

(2) Twenty-four square foot sized pond, solar heat added, heat storage.

(3) Standard size pond, solar heat added, no heat storage.

(4) Standard size pond, heat collected passively by glass cover stimulating a greenhouse effect.

(5) Standard size pond, solar heat added, heat storage.

(6) Eleven square feet sized pond, solar heat added, heat storage.

Solar collectors used for heat additions were of the liquid heating type. Sixteen square feet of collector was used per pond.

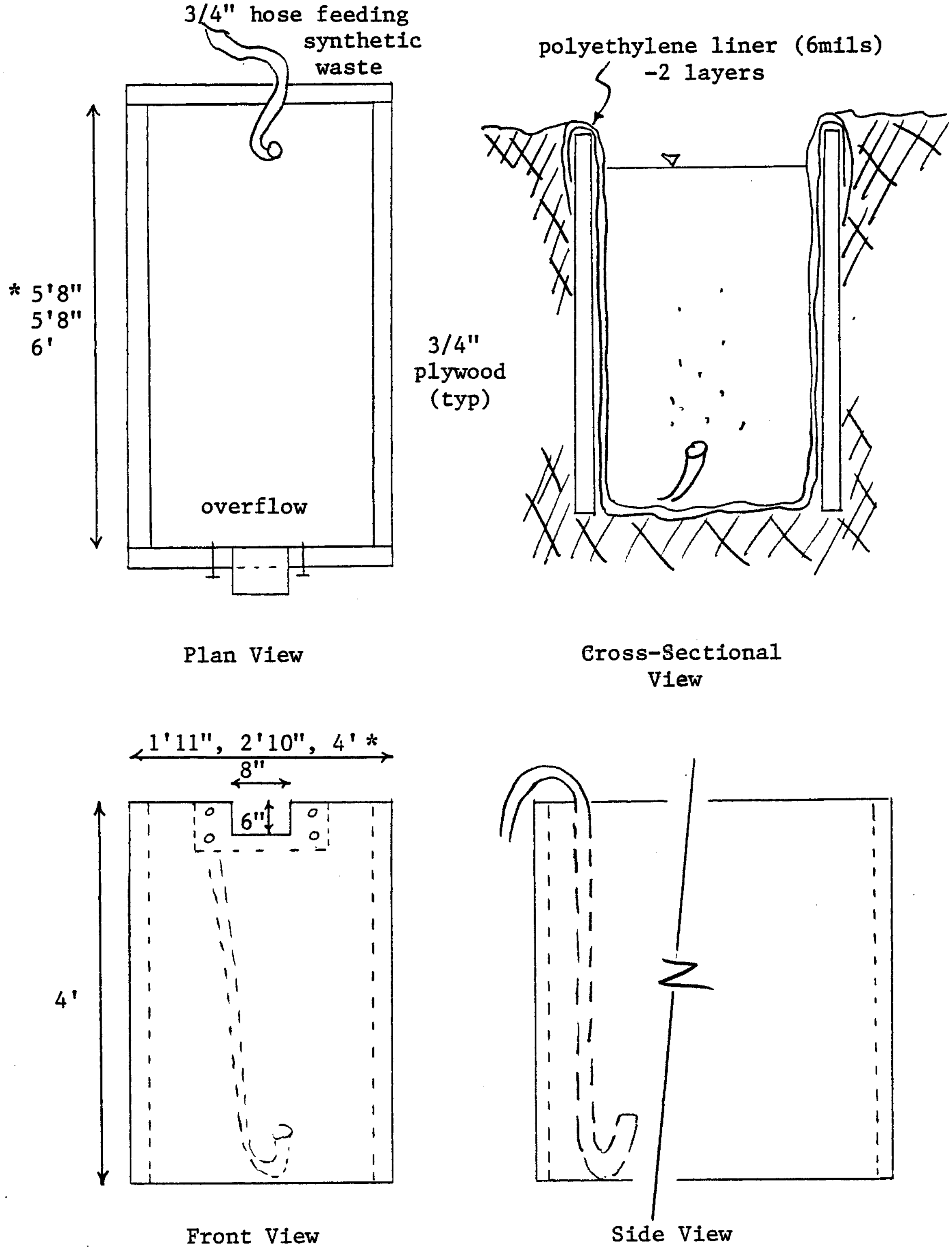

Figure 3-3. Typical Model Pond Construction
* variable dimensions in order of 11,16, and 24 sq. ft. sized ponds.

3.4 Experimental Apparatus

Experimental apparatus used for solar heat collection, storage and transfer to the model ponds may be depicted as three individual systems. Briefly, these were:

(1) Solar collector - pond.

(2) Solar collector - heat storage - pond,

(3) Transparent cover over pond.

Schematic diagrams of the experimental apparatus used in Systems 1 and 2 above are shown in Figures 3-4 and 3-5, respectively. The third system is shown in Figure 3-2b.

Flat plate collectors typical of equipment Systems 1 and 2 are shown in Figure 3-2c. Two collectors, one 12 ft^2 (2' x 6'), the other 8 ft^2 (2' x 4'), were used in each system. Hydraulically, they were connected in series, with hot water from the smaller one flowing into the larger. Collectors were made by Rocky Mountain Sheet Metal Company of Denver, Colorado, and had the following characteristics.

(1) Gross area = 20 ft^2

(2) Effective area = 16 ft^2

(3) 20/80 glycol/water mixture

(4) Low iron oxide glass

(5) Transmittance = 89.1 percent

(6) Absorptance = 0.95

(7) Emissivity = 0.08

Collectors were mounted at a 55° angle to the horizontal on two insulated plywood sheds that housed all electrical components of the project.

Flow through the systems was controlled by a Honeywell differential temperature controller, Model Number R7412. Pump turn on by these

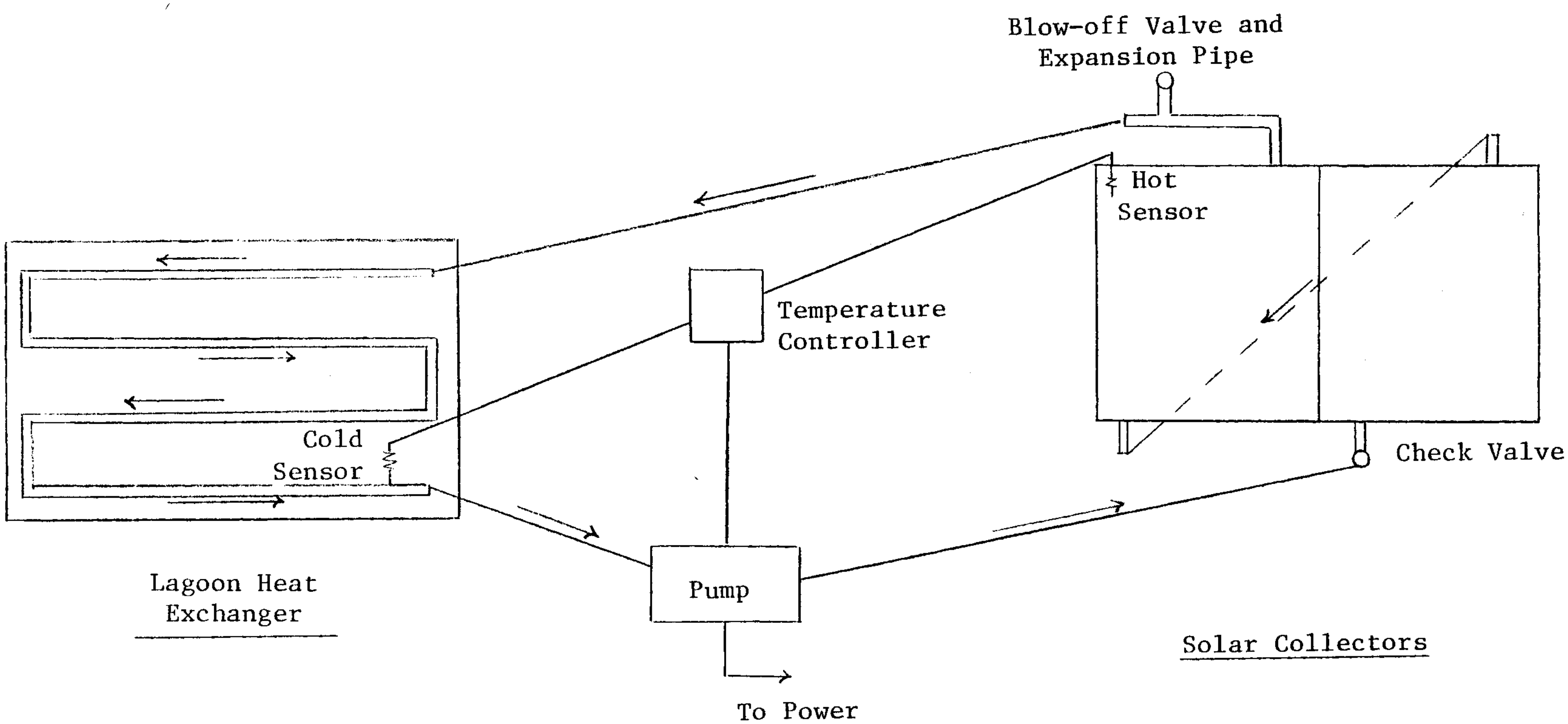

Figure 3-4. Schematic of Equipment Apparatus; System 1.

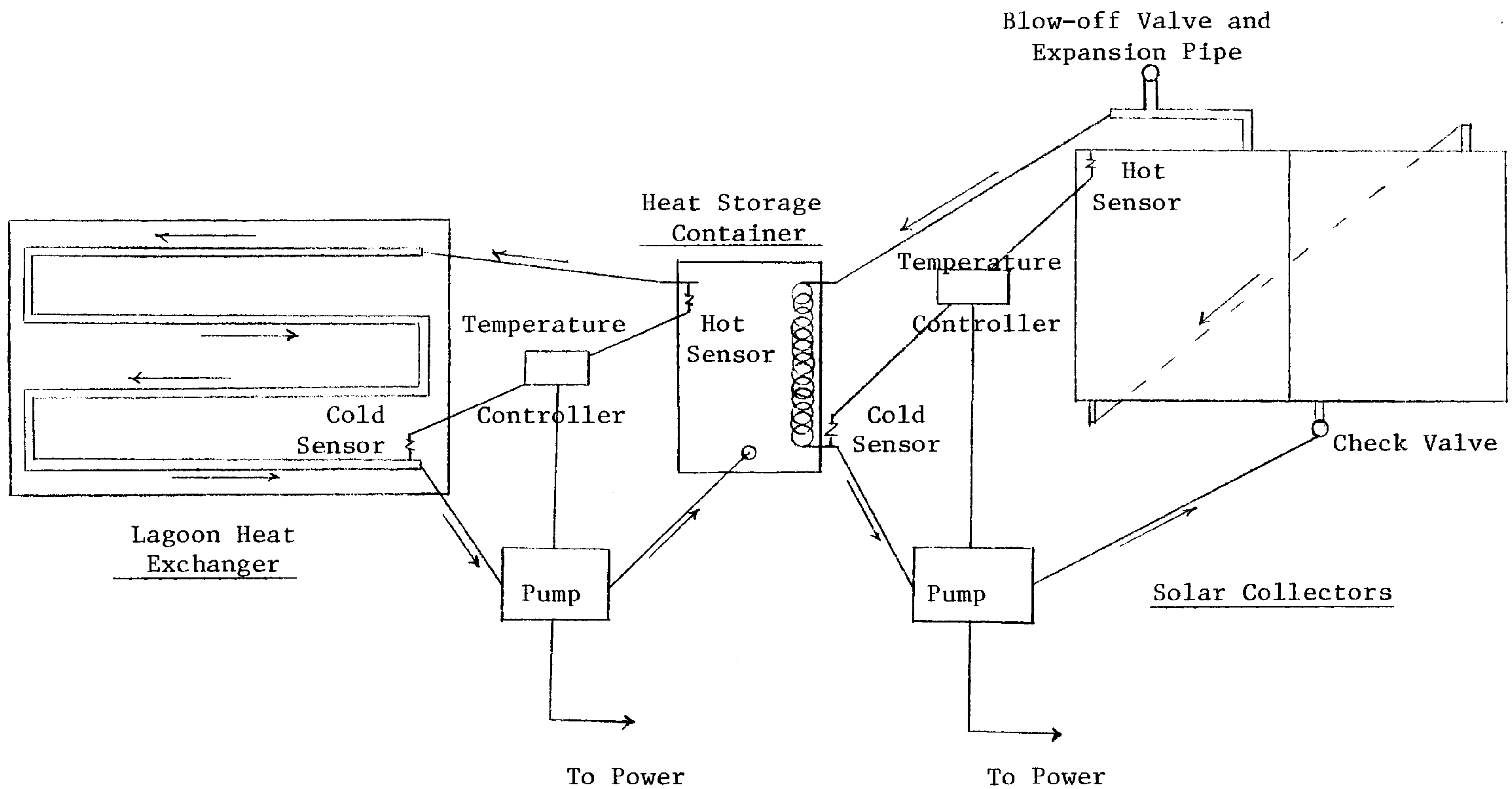

Figure 3-5. Schematic of Equipment Apparatus; System 2.

controllers occurred when the water temperature difference between sensors became greater than 18°F (10°C). It turned off when this temperature difference reduced to 3°F (1.7°C). Honeywell electronic temperature sensors, Model Number C773, were used in conjunction with these controllers.

In systems utilizing heat storage, the hot sensor was clipped to the top underside of the absorber plate and cold sensor was mounted in an immersion well at the cold exit end of the heat storage unit. This arrangement regulated heat transfer to the storage unit. The hot sensor of the comparator, regulating heat flow to the pond was clipped to the top end of the heat storage unit near the hot water exit. The corresponding cold sensor was mounted in an immersion well at the cold end of the pond thermal exchanger. In systems without heat storage, the hot sensor was clipped to the absorber plate and the cold sensor mounted in an immersion well at the cold end of the pond thermal exchanger.

A typical heat storage unit, during construction, is shown in Figures 3-6a, 3-6b, and 3-6c. The interior of the box was painted with fiberglass to prevent leakage. To minimize heat losses, these heat storage systems were placed in a plywood frame, filled with dirt and hay, and partially buried. Design guidelines specified for the storage unit were two gallons per square foot of collector area. The liquid volume of the unit was 32 gallons.

All pumps were five speed, variable speed, Teel water circulation pumps, Model Number 1P965, with a maximum horsepower and a maximum speed of 1/20 hp and 2,000 rpm, respectively. Pumps were operated at about 8 gpm under about 10 to 12 feet of head.

Heated liquid was cycled to the system components via a 3/4-inch garden hose. The hose was connected to 3/4-inch copper tubing at each

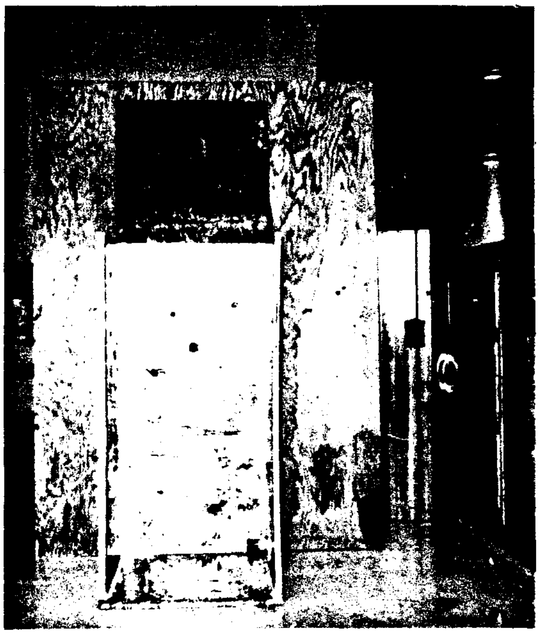

Figure 3-6a. Heat Storage Unit; Interior View Without Heat Exchanger

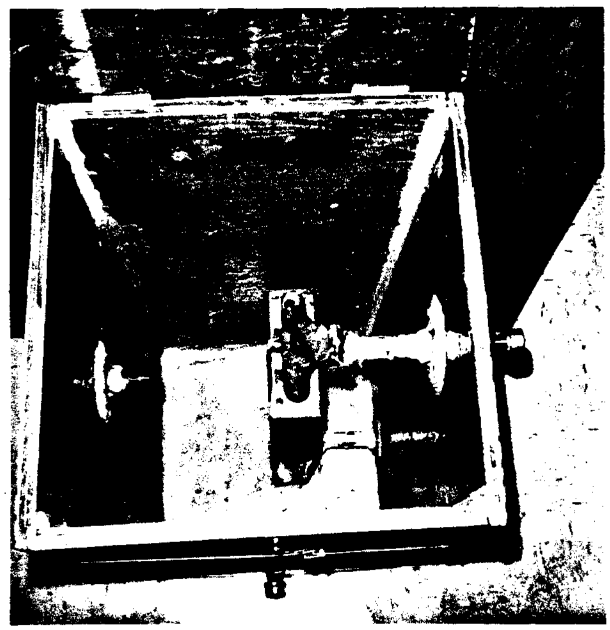

Figure 3-6b. Heat Storage Unit; Top View

Figure 3-6c. Heat Exchanger

Figure 3-6. Heat Storage Unit With and Without Heat Exchanger system component. All exposed hose or copper lines were wrapped with fiberglass insulation to an R value of 40. The insulation was waterproofed by wrapping it in polyethylene. Heat transfer to the ponds was by means of a 3/4-inch copper coil thermal exchanger. A typical coil is shown in Figure 3-2d. Coils were constructed to fit the individual lagoons, therefore, the coil sizes for the larger and smaller lagoons were slightly different from the standard sized coils. All coils, connections, and lines were air tested for leaks prior to operation and monitored for leaks throughout the test.

Glass used to cover the passive lagoon system completely covered the lagoon, resting about six (6) inches above the water level, as shown in Figure 3-2b.

3.5 Synthetic Waste

The synthetic waste mixture used in this work was proportioned from a mixture used in a similar study.[22] The mixture consisted mainly of powdered milk* and dry dog food**. Nitrogen and phosphorus in the form of NH_4Cl and Ha_3PO_4 were added to insure that carbon was not the limiting nutrient.

To prepare the waste mixture, 90 grams of dog food was placed in 500 ml of distilled water and allowed to soften for one hour. The dog food and water was then mixed in a blender and diluted to two liters with distilled water. After settling the supernatant was decanted off. To this mixutre, 200 grams of powdered milk was added to make the concentrated waste mix. Seven hundred ml of this concentrated waste mix was mixed, in a 55-gallon drum, with 40 gallons of water,

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*Pet Instant Non-fat Dry Milk
**Gaines Gravy Train

5.8 grams of NH_4Cl, and 0.6 grams of Na_3PO_4 to obtain the mixture fed to the ponds. The final mixture was pumped from the drums to the ponds. Characteristics of the proportioned waste mixture are shown in Table 3-1.

Table 3-1

Characteristics of Synthetic Waste Influent to Ponds

Ingredient	Quantity
BOD	330 mg/l
NH_4Cl as N	10 mg/l
Ha_3PO_4 as P	2 mg/l

3.6 Pond Operation and Sampling Procedures

Ponds were initially seeded with a wastewater mixture, taken from A-basin of Fort Collins Wastewater Treatment Plant No. 2. Synthetic waste was pumped to the ponds from a 55-gallon drum every other day. The hydraulic loading rate was 35 lbs BOD per acre per day. Wastewater entered the pond as shown in Figure 3-3, approximating a plug flow regime. Ponds were faculative for the duration of the test.

Parameters monitored in this study were temperature, BOD, and DO. Temperature was the main variable of interest in this study and, therefore, was monitored continuously. Temperature for each point was recorded every 2.4 minutes on a Leeds and Northrup Speedomax multichannel recorder. Eight channels were used to record temperatures. Temperatures recorded were:

- all pond temperatures at a depth of one foot below the water surface

- ambient air temperature
- heat storage temperature near the outlet

Only one heat storage temperature was monitored continuously. Checks were made periodically with other storage units to compare temperatures of these units.

BOD and DO tests were conducted but were not the primary variables of interest in this study. Their use at this point was to get a feel of what was happening in the pond as a result of the temperature increases. BOD samples were taken every other day at about 4:00 p.m., prior to feeding. BOD tests were run to obtain a comparative estimate between ponds of pond performance. DO and temperature profiles were monitored periodically to estimate mixing capabilities of the pond. Profile measuring points were the water surface, mid-depth and four inches off of the pond bottom. Profiles were monitored twice during the test period at two-hour intervals and other times at noon and midnight. The test period in which these variables were monitored was the months of April and May, 1980. All tests were conducted in accordance with procedures outlined in Standard Methods for the Examination of Water and Wastewater, 14th Edition.

SECTION 4

MATHEMATICAL ANALYSIS

4.1 General

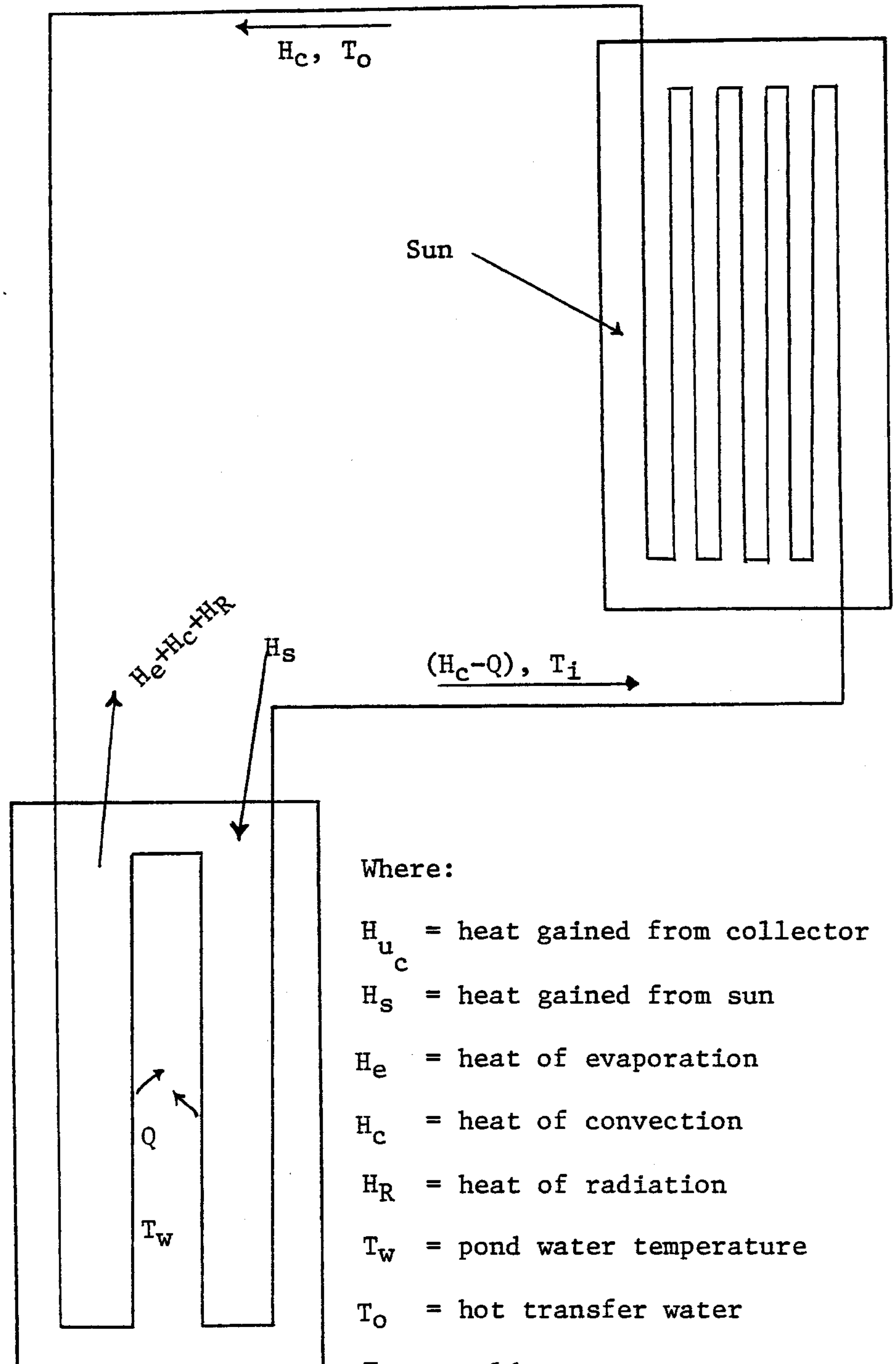
To obtain a relationship applicable to predicting pond temperatures, it is necessary to account for all heat originally present in the pond, and all heat that flows into or out of the pond during the time interval of interest. Figure 4-1 depicts the heat quantities pertinent to the solar heated waste stabilization pond. Initially the pond contains sensible heat. Heat gained from the solar collector is added to this initial quantity. Heat is lost from the surface area of the pond due to the effects of various atmospheric conditions such as air temperature, relative humidity, cloud cover, wind speed, barometric pressure, etc. Several different heat transfer phenomena are accounted for in the water temperature computation and are functions of the variables mentioned above. The following discussion presents these heat transfer phenomena and the underlying analytical concepts for the solar heated stabilization pond model.

4.2 Solar Energy Available

The use of solar energy to maintain stabilization pond temperatures is dependent upon how much solar energy is available for the collector to trap. This, in turn, is dependent on many climatic and environmental factors as discussed in Section 2.4.

The following equation was used to calculate the amount of useful energy trapped by a solar collector.[17,28]

$$H_{u_c} = A_c \left[H_T \, T \, F_R - U_L \, F_R \, (T_i - T_a) \right]$$



Where:

H_{u_c} = heat gained from collector

H_s = heat gained from sun

H_e = heat of evaporation

H_c = heat of convection

H_R = heat of radiation

T_w = pond water temperature

T_o = hot transfer water

T_i = cold return water

Q = heat transterred to pond

Figure 4-1. System Heat Flows

where:

H_{u_c} = rate of useful heat transfer to the working fluid in the solar exchanger Btu/hr

F_R = collector heat removal factor, dimensionliess

A_C = surface area of collector, ft^2

H_T = Btu/hr - ft^2 collector receives on a surface titled at a particular angle

T = transmittance - adsorptance product, $\gamma\alpha$, dimensionless

U_L = heat losses, Btu/hr-ft^2-°F

T_i = temperature of fluid going into collector

T_a = ambient temperature

The optimum tilt angle for winter months is the latitude of the location plus 15°.[28] Values for T F_R and U_L F_R used in this study were 0.75 and 0.85, respectively.

Figure 4-2 provides a definitive sketch of this equation.[28] F_R, γ, α, and U_L are fixed for a given collector. Values used were provided by the manufacturer. Collector area, A_c, is also fixed making the solar radiation term, H_T, and the air temperature, T_a, the independent variables of the equation.

Because solar radiation is so variable throughout the day, it is not suitable to predict detailed collector and pond performances using long-term monthly averages of solar radiation.[17,28] Hourly fluctuations should be accounted for. Daily averages can at best lead to a rough approximation of the heat gained. The approach adapted to the computer model developed for this study uses average hourly solar radiation

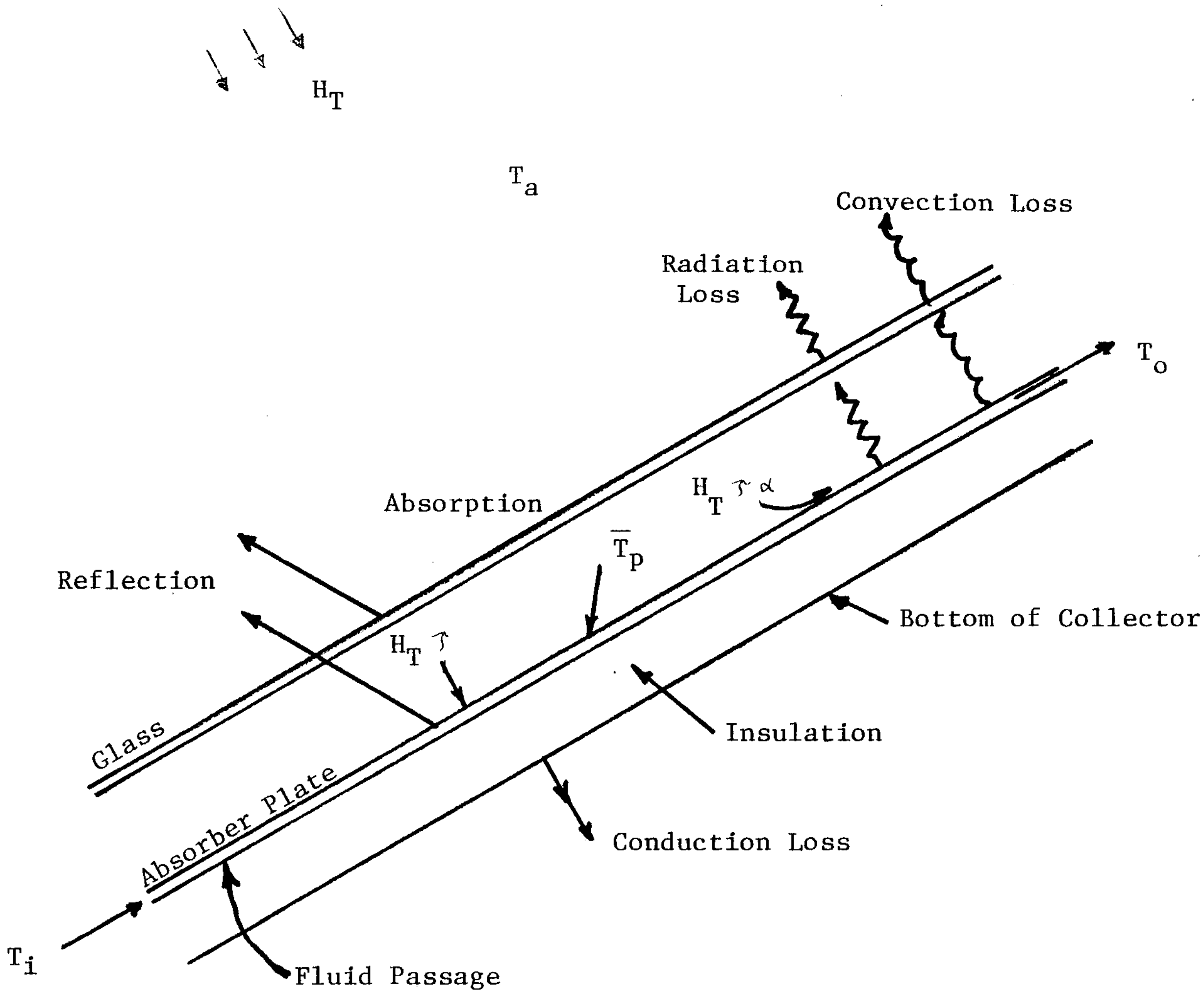


Figure 4-2. Definition Sketch for Equation 4.1.

data to predict average hourly pond temperatures. These predictions were then compared with experimental results. The computer model can also use monthly daily solar radiation averages for rough daily pond temperature approximations.

4.3 Heat Transferred to Pond

The amount of solar heat collected that can be transferred to the pond is a function of the convective, conductive, and geometric properties associated with the heat exchanger lying on the pond bottom, the heat exchanger fluid, and the pond water. The rate of heat transfer between the fluid in the exchanger and the pond water may be written as follows:

$$Q = UA\Delta T_m$$

where:

Q = Btu/hr transferred to the pond

U = overall heat transfer coefficient, Btu/ft^2-hr-°F

A = area of pipe wall normal to the direction of heat flow, ft^2

ΔT_m = log mean temperature difference between the exchanger fluid and the pond water, °F

The overall heat transfer coefficient, U, encompasses the heat flows by convection and conduction processes in series. The computer model developed for this study assumes that essentially all of the heat trapped by the collector is transferred to the pond. It is realized that this approach is not theoretically correct but it provides an upper limit that reasonably approximates model pond temperature processes.

4.4 Heat Losses

To determine the amount of useful energy put into the pond to raise the water temperature, heat losses must be subtracted from the energy transferred to the pond. The following discussion centers on the equations used to determine heat losses.

Evaporative Heat Losses, H_e. Evaporation from the water surface will cause a loss of heat from the pond to a depth of about ten feet. The evaporation equation is:[32]

$$I = C_1(1 - 0.1W)(V_w - V_a)$$ Meyer's Formula for Evaporation

where:

I = evaporation from natural water bodies, inches/month

W = mean wind velocity, mph @ 25 feet

V_w = water vapor pressure, inches of mercury using surface water temperature one foot below surface

V_a = mean absolute water vapor pressure @ 25 feet and relative humidity

C_1 = constant, ranges from 10 to 15; large deep lakes and reservoirs, use 10; shallow ponds and surface accumulations, use 15

Using latent heat of vaporization, H_v, for a given water temperature, I, in inches per month is converted to H_e, loss in Btu per hour per square foot of water surface by:[32]

$$H_e = 0.00722\, H_v C_1 (1 + 0.1W)\ (V_w - V_a)$$

where:

H_e = evaporation heat loss, Btu/hr-ft^2

H_v = latent heat of vaporization, Btu/hr-ft^2, (Table 4-1)

C_1 = constant, 15 for shallow ponds

W = mean wind speed, mph

V_w = water vapor pressure, inches of Hg (Table 4-2)*

V_a = mean absolute water vapor pressure (Table 4-2)*

Convective Heat Losses, H_c. Convection is dependent upon the wind velocity, the mixing of the water within the pond, and temperature gradient between the pond and ambient air. Convective heat losses are determined by:[32]

$$H_c = (C_3 + C_2 \frac{W}{2}) (T_w - T_a)$$

where:

H_c - convective heat loss, Btu/hr-ft^2

C_2 = constant = f (water body)

quiescent body of water - 0.16

relative quiescent body - 0.24 (typically used)

C_3 = convective losses from flat surfaces

0.5 Btu/hr-ft^2 °F - T few degrees

0.8 Btu/hr-ft^2 °F - typical

1.0 Btu/hr-ft^2 °F - T 50 to 100°F (used)

W = surface wind velocity, mph - Use $\frac{W}{2}$ in equation when using Weather Bureau measurements and W when field measurements

T_w = surface water temperature, °F

Radiation Heat Losses, H_R. The pond water acts as a warm body which radiates heat to the colder atmosphere during most of the year. A simplified equation for this loss is:[32]

$$H_R = (T_w - T_a)$$

*Both V_w and V_a are based on saturated water vapor pressure at a given temperature.

TABLE 4-1. LATENT HEAT OF VAPORIZATION H_v

T(°F)	H_v(Btu/lb)	T(°F)	H_v(Btu/lb)
32	1,075.8	100	1,037.2
35	1,074.1	105	1,034.3
40	1,071.3	110	1,031.6
45	1,068.4	115	1,028.7
50	1,065.6	120	1,025.8
55	1,062.7	125	1,022.9
60	1,059.9	130	1,020.0
65	1,057.1	135	1,017.0
70	1,054.3	140	1,014.1
75	1,051.5	145	1,011.2
80	1,048.6	150	1,008.2
85	1,045.8	155	1,005.2
90	1,042.9	160	1,002.3
95	1,040.1	165	999.3

Source: Velz, Applied Stream Sanitation, p. 283

TABLE 4-2. SATURATED WATER VAPOR PRESSURE V_a IN INCHES H_g

Air T (°F)	Vapor Pressure (in. Hg)	Air T (°F)	Vapor Pressure (in. Hg)	Air T (°F)	Vapor Pressure (in. Hg)	Air T (°F)	Vapor Pressure (in. Hg)
30	0.164	60	0.157	90	1.408	120	3.425
31	0.172	61	0.536	91	1.453	121	3.522
32	0.180	62	0.555	92	0.499	122	3.621
33	0.187	63	0.575	93	1.546	123	3.723
34	0.195	64	0.595	94	1.595	124	3.827
35	0.203	65	0.616	95	1.645	125	3.933
36	0.211	66	0.638	96	1.696	126	4.042
37	0.219	67	0.661	97	1.749	127	4.154
38	0.228	68	0.684	98	0.803	128	4.268
39	0.237	69	0.707	99	0.859	129	4.385
40	0.247	70	0.732	100	1.916	130	4.504
41	0.256	71	0.757	101	1.975	131	4.627
42	0.266	72	0.783	102	2.035	132	4.752
43	0.277	73	0.810	103	2.097	133	4.880
44	0.287	74	0.838	104	2.160	134	5.011
45	0.298	75	0.866	105	2.225	135	5.145
46	0.310	76	0.896	106	2.292	136	5.282
47	0.322	77	0.926	107	2.360	137	5.422
48	0.334	78	0.957	108	2.431	138	5.565
49	0.347	79	0.989	109	2.503	139	5.712
50	0.360	80	1.022	110	2.576		
51	0.373	81	1.056	111	2.652		
52	0.387	82	1.091	112	2.730		
53	0.402	83	1.127	113	2.810		
54	0.417	84	1.163	114	2.891		
55	0.432	85	1.201	115	2.975		
56	0.448	86	1.241	116	3.061		
57	0.465	87	1.281	117	3.148		
58	0.482	88	1.322	118	3.239		
59	0.499	89	1.364	119	3.331		

Source: Velz, Applied Stream Sanitation, 1970, p. 289

Solar Radiation Heat Gains, H_s. While all of the other factors considered have removed heat from the water body, the energy from the sun adds heat to the water. The following equation was used to determine solar radiation heat gains:[32]

$$H_s = SR \times f$$

where:

H_s = solar radiation gain, Btu/hr-sq ft

SR = solar radiation, Btu/hr

f = adsorption coefficient at surface 0.95

Advection Heat Transfer, H_a. The water movement into and out of the pond from the surrounding soil also carries heat with it. However, this heat transfer is considered insignificant and therefore has been neglected.

Heat Losses from Piping, H_p. Pipes were well insulated in this study and therefore pipe heat losses were ignored.

Total Heat Loss, H_T. The total of the natural heat losses and gains are summarized below:

$$H_T = H_e + H_c + H_R - H_s$$

4.5 Energy Balance

The energy balance for the pond of Figure 4-1 is summarized as follows:

$$H_{u_s} = Q + H_s - H_p - H_e - H_c - H_r$$

where:

H_{u_s} = change in Btu/hr of the system

H_{u_c} = useful Btu/hr collector receives

Q = Btu/hr transferred to the pond

H_s = radiation lagoon receives directly from sun

H_p = heat loss from pipes

H_e = heat loss from evaporation

H_c = heat loss from convection

H_R = radiation loss

Under steady-state conditions, H_{u_s} would be equal to zero and the energy balance equation becomes:

$$Q = H_p + H_e + H_c + H_R - H_s$$

In addition, if there were 100 percent transfer of all heat collected by the solar collector to the pond, Q would equal H_{u_c} and the energy balance for the pond would become:

$$H_{u_c} = H_p + H_e + H_c + H_R - H_s$$

As discussed previously, the complete model makes this assumption.

4.6 Computer Model

Finding solutions to the heat balance equations presented in the previous sections would be a laborious, endless task if attempted by hand. Consequently, a computer model was developed to aid in manipulation of these equations. The model is titled SOLAR HEATED STABILIZATION PONDS TEMPERATURE ANALYSIS. It's purpose is to evaluate the heat balance of the stabilization pond system and predict pond temperatures for given collector area, flow rates, pond size and climatic conditions. It has an additional option of calculating pond surface area required to maintain a given temperature. In developing the model some assumptions and modifications were made regarding the equations, to assure consistency of operation within the computer model. Some of these have been noted already in the previous sections. The following discussion presents details of the computer model. Use of the model is presented in Appendix C. The model itself may be found in Appendix B.

Pond and collector data. The data input for each collector/pond system includes: solar collector flow rate, solar collector characteristic coefficients TF_R and U_LF_R, solar collector area, pond depth, pond area and initial pond water temperature. Any specific conditions can be evaluated by changing one of these program cards. The model will sequentially evaluate a number of different system conditions during the same computer run.

Climatic conditions. The principal factors that affect the heat loss calculations are the wind speed, ambient air temperature, relative humidity, and solar radiation. These are site specific factors that must be obtained for each site, or at least in the general locale.

Equation factors. A number of factors must be computed by the computer for use in the heat loss equations. Two of these are vapor pressure and heat of vaporization. Since both of these factors are temperature dependent, it was necessary to develop an approximation equation for each rather than putting the entire tables of data in computer memory.

Plotting the data for the Latent Heat of Vaporization, H_v, a straight line plot was obtained which yielded the equation:

$$H_v = 1{,}094 - 0.57\ (^{\circ}F)$$

The plot of the saturated vapor pressure data versus temperature yielded a higher level exponential curve. The simplified form of the equation is:

$$VP = 0.0498 \; (\exp \; (^{o}F))^{0.0375}$$

Another factor, C_3, which relates to the convective losses from flat surfaces, was entered as input data but can be computed using the equation:

$$C_3 = 0.5 + 0.01 \; (^{o}F) \qquad \text{Valid RAnge } (0^{o}F \text{ to } 50^{o}F)$$

Above $50^{o}F$, the value is set at $C_3 = 1.0$ and below $0^{o}F$ the value is set at $C_3 = 0.5$.

Pond water temperatures. The final temperature of the pond water is determined by iteration with the net heat losses of the pond due to climatic conditions and the net heat input from the solar collector. An equilibrium condition is achieved, for each time period evaluated, by iterating 15 times all of the calculations, as the pond temperature changes to reach the equilibrium points. Once equilibrium is reached between the heat losses and gains, this temperature is used to initialize the pond temperature for the next period's calculations.

Area required to maintain a specific pond water temperature. Given a desired pond water temperature and collector system the net heat gains and losses are determined. On this basis, it is possible to calculate the pond surface area that can be maintained at this temperature.

Model outputs. The first table given in the output is the temperature profile of the pond for specific site and system conditions throughout the year or day, whichever is evaluated. The second table presents the pond surface area in square feet that can be supported at a given site for the temperatures indicated. The program will also summarize heat transfer quantities and pond water temperatures if called on to do so.

SECTION 5

RESULTS AND DISCUSSION

5.1 General

Analysis of the data collected from the six model ponds, the computer model predictions and comparison of the experimental models with the computer model are presented in this chapter. Experimental results, computer model data and computer model results are summarized in Appendices A, D, and E, respectively.

5.2 Experimental Ponds

Temperature, dissolved oxygen (DO), and biochemical oxygen demand (BOD) characteristics of the model ponds monitored during the study are discussed in this section. Temperature data recorded continuously by the multi-channel recorder have been reduced to monthly hourly averages and monthly daily averages for the two months of record. Average daily temperatures of the six model ponds for the months of April and May 1980 are shown in Table A-1 of Appendix A. Graphical portrayals of the diurnal temperature variations, based on monthly hourly averages for the test period, are shown in Figures A-1 through A-4. Figures A-5 through A-16 show temperature and DO variations with depth, for a typical day, for each of the six ponds.

The diurnal temperature variations shown in Figures A-1 and A-2 compare the three different systems tested (solar heat added, no heat storage, solar heat added via heat storage container glass covered system) to that of the control pond. The system with solar heat added directly to the pond obviously had higher average temperatures throughout the day than the ponds of the other systems analyzed. Temperatures in this pond were, on the average, 8.5°F (4.7°C) higher than in the control pond.

Attempts to store heat overnight use did not prove as effective. Temperatures were greater than that of the control pond, but were 2.7°F (1.5°C) less than those of the system adding solar heat directly. Reasons can -e attributed to a combination of excessive heat losses from the system, inadequate design of the heat storage unit and less effective heat transfer between heated storage unit and the heated collector fluid. Improvement in the system design may reduce or eliminate the temperature difference, but it is doubtful that the added heat benefits would be significant enough from a practical, cost effective point of view to warrant further infestigation of this alternative. The pond volume iself serves as an effective heat storage sink.

Referring again to Figures A-1, A-2, and Table A-1, the effect of adding a glass cover, simulating a "greenhouse" effect, did very little in this study to raise the overall pond water temperature. Pond water average temperature was lower than the control pond ans shows only slight variation in temperature throughout the day. In addition, Figure A-8 indicates that the effect is to severely stratify the pond. Save for the upper most pond layer (top 6"), the pond undergoes little warming. In view of the fact that a pond's effectiveness is dependent upon pond bath temperature and mixing, it is doubtful that this pond fairs as well as the control pond in wastewater treatment.

Figures A-3 and A-4 compare the pond temperature characteristics of three different sized ponds with the same amount of solar heat added to each. As expected, the smallest sized pond was the warmest throughout the average day, but only by an average of 2.2°F (1.2°C) over the largest sized pond (2.2 times larger). The significance of this in terms of treatability is a goal of further study.

In viewing the diurnal temperature and DO profiles for a typical day, shown in Figures A-5 through A-16, it is clear that there was a lack of thermal stratification in the solar heated ponds during the test months. Temperatures of the solar heated ponds show little variability from top to bottom throughout the day, save for the upper most top thin layer which gets relatively hot during daylight periods. In addition, temperature of the lower portions of the solar ponds are considerably warmer than those of the control pond. Coupling these observations with the observance of higher relative DO levels at lower depths, it can be reasoned that heat added from the coils on the pond bottom resulted in more extensive thermal mixing of the pond layers.

Surface waters follow a cycle of heating during the day and cooling at night. Daily mixing can be attributed to a slow roll of convective currents rising from the heat exchanger. At night the upper layer cools and mixes with the rest of the pond as the heavier, cooler waters sink to lower depths. The top surface layer at night, at times, even becomes slightly cooler than the rest of the pond. The fact that in the solar heated ponds there are relatively higher DO values at all times at lower depths than in the control pond, supports this thermal mixing theory.

Results of the BOD tests are shown in Table A-2. Information available from these tests is inconclusive. Effluent BOD's of the solar heated ponds do not tend to be significantly less than those of the control ponds, as would be expected. The results may be explained by the lower overall DO values found in these ponds and the fact that all ponds were seeded prior to testing with a wastewater that contributed quite a sludge load to the ponds. What appears to have happened is that the oxygen demand in the solar heated ponds was so much greater because additional products of anaerobic fermentation were being added to the liquid portion of the pond, that the mass quantity of BOD reduced was masked. To eliminate this factor it would be necessary to run the tests over quite a longer period of time, say a year or more, to assure that the sludge BOD is used up. Another alternative would have been to have started with a fresh, unseeded pond, and feed it periodically for several months with synthetic waste, until a population had established itself. In addition, future testing should include suspended solids, algal assays, BOD's on filter samples, etc., to attempt to determine what portion of the BOD is due to algae and what can be attributed to soluble BOD.

5.3 Computer Model

Computer model results are discussed and compared to the experimental results in this section. The model was run using input data typical of the experimental site and surrounding area. This included both actual test site data taken during the experimental portion of this study and long term average daily data indicative of the area. A graphical presentation of the monthly daily temperature averages predicted by the model for both systems with and without solar collectors is found in Figure E-1 of Appendix E. Diurnal temperature model predictions are graphically compared to actual experimental results in Figures E-2 and E-3, for the months of April and May respectively. Table E-1 summarizes predicted pond surface areas that will be maintained at specified pond water temperatures. The model predicts temperatures for a pond with heat inputs characteristic of experimental pond no. 3 and these predictions are compared to this pond.

Average daily temperature predictions for each month of the year, summarized in Figure E-1, show temperatures of the solar heated pond on the average 5.1°F (2.8°C) higher than that of the non-heated pond. In addition, the model predicts average daily pond water temperatures of solar heated ponds above freezing during the colder months. Results predicted by the model for the solar heated pond are on the order of 4.3°F (2.4°C) higher than the experimental results when summarized as a daily average. The April predicted temperature was 4.7°F (2.6°C) greater than the average daily temperature of pond no. 3 for that month. The May predicted temperature was 3.9°F (2.1°C) higher than the experimental results.

When model temperature predictions for the natural ponds are compared to the results recorded for the experimental control pond, however, the temperature spread is much greater. Here the April predicted temperature average was 7.3°F (4.1°C) greater than the average daily temperature of the control pond. The May predicted temperature was 8.5°F (4.7°C) higher than the experimental results. Reasons for these discrepancies can be attributed to the fact that ambient air temperatures were lower than normal during the test period. In addition, it was unusually rainy and overcast during this period. With these facts in mind it can be reasoned that the average daily temperatures predicted by the model seem to provide a reasonable upper limit for solar heated pond water temperature expectations. In that there are only two months of data with which model predictions have been compared to however, further study and comparisons are in order. These studies should extend over a period of at least one year.

The area calculations summarized in Table E-1 are also based on long term average daily data and therefore provide a reasonable range of what to expect in this accord. Table E-1 indicates that for a relatively small collector area rather large pond surface areas may be maintained at specified water temperatures. These results support the need for further investigation of this treatment alternative.

Referring to Figures E-2 and E-3 it can be seen that hourly predictions compare very poorly with the experimental results. Neither the amplitude nor the location of the high and low temperatures coincide. One problem could be that the equations used in the theoretical analysis were developed based on an average daily basis rather than average hourly and therefore do not accurately model the daily cycle. Further work needs to be done in this area to correctly model the daily cycle. This would involve a study of the present equations and the possibility of revising them or investigating new equations to model the daily cycle.

SECTION 6

CONCLUSIONS

Objectives of this phase of the study have been fulfilled. Conclusions drawn from the study to date are summarized as follows:

(1) Heat trapped by a flat plate collector and transferred directly to the pond via a heat exchanger apperaed to be the most practical system suited to raising pond temperatures. Test results, for April and May 1980, show it possible to raise pond temperatures over those of a control pond, 8.5°F (4.7°C), using a collector area equal to the pond area. Theoretical analysis yielded average pontential temperature increases for similar situation of 5.1°F (2.8°C) and average pond temperatures above freezing in the colder months.

(2) The size of pond a given collector system is capable of heating to to a specified temperature has been estimated through the use of the computer model. At this point in the study, the size of collector system to pond area relation based on treatment performance, has not been determined. Continued study, emphasizing treatability, is necessary to logically predict a practical, functional relation between collector size and pond size for a given location.

(3) Heat storage did not prove beneficial over nonstorage in this study. Even with improved storage tank design, the author doubts that it would be economically realistic on a large scale basis. The pond itself serves as a heat sink. Deeper ponds should be investigated.

(4) The addition of a transparent cover to a pond to reduce heat loss did not improve pond performance in this study. The pond remained highly stratified, colder in the lower depths, and did not make effective use of pond capacity. It is believed that over the long term, excessive sludge accumulation would occur and pond apparent treatability performance would greatly diminish.

(5) The addition of solar heat to a waste stabilization pond substantially increased the pond's performance through increased mixing and warmer overall pond temperatures. In this way more effective use is made of the total pond volume

(6) The computer model does not appear to accurately model the daily cycle. Further study in this area is in order.

SECTION 7

RECOMMENDATIONS FOR FURTHER STUDY

Solar heated waste stabilization ponds have been indicated to a viable means of improving pond performance, As such, treatment of wastes by this method warrants continued investigation. Recommendations for further study include:

(1) Study should be continued over the period of at least one year using the synthetic waste. Over a period of this length BOD from the sludge seed would be used up, thereby eliminating the dampening effect sludge fermentation has on measured BOD reduction. Doing this would result in comparable mass wastage rates for each type of pond.

(2) Repeat the above for actual municipal sewage as the influent substrate.

(3) Expand the computer model to predict BOD reductions using known relationships for substrate utilization and temperature. Model can also be expanded to include predictions of pond bottom temperatures and effects of anaerobic processes.

(4) Neglect heat storage systems and passive systems in the next study.

(5) Examine the effects of increased pond depth on pond temperature and treatment characteristics,

(6) Reduce the number of ponds tested and increase the number of monitoring points through the pond depth. This will enable continuous tracking of the temperature profile and show the degree of mixing over the long term.

(7) Additional variables should be tested to obtain a more accurate picture of what is happening in the ponds. These should include, but not be limited to: pH, alkalinity, algal assays, and suspended solids.

(8) Continue study on the computer model with comparisons to actual test site data. Model equations may need to be refined to more accurately predict the real situation.

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APPENDICES

APPENDIX A

EXPERIMENTAL RESULTS

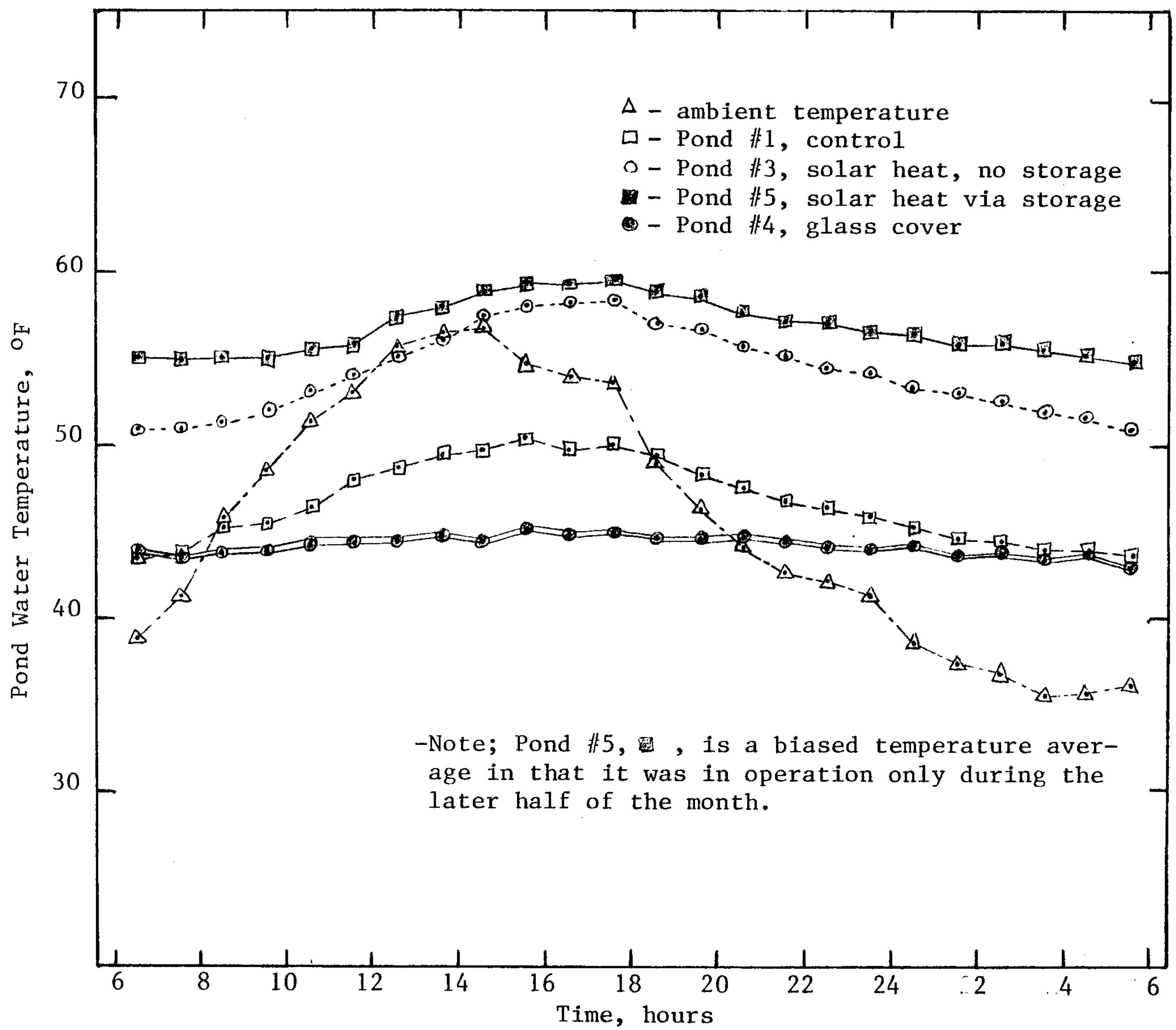

Figure A.1. Experimental Ponds: Average Daily Pond Water Temperature Cycle, April 1980-System Comparison

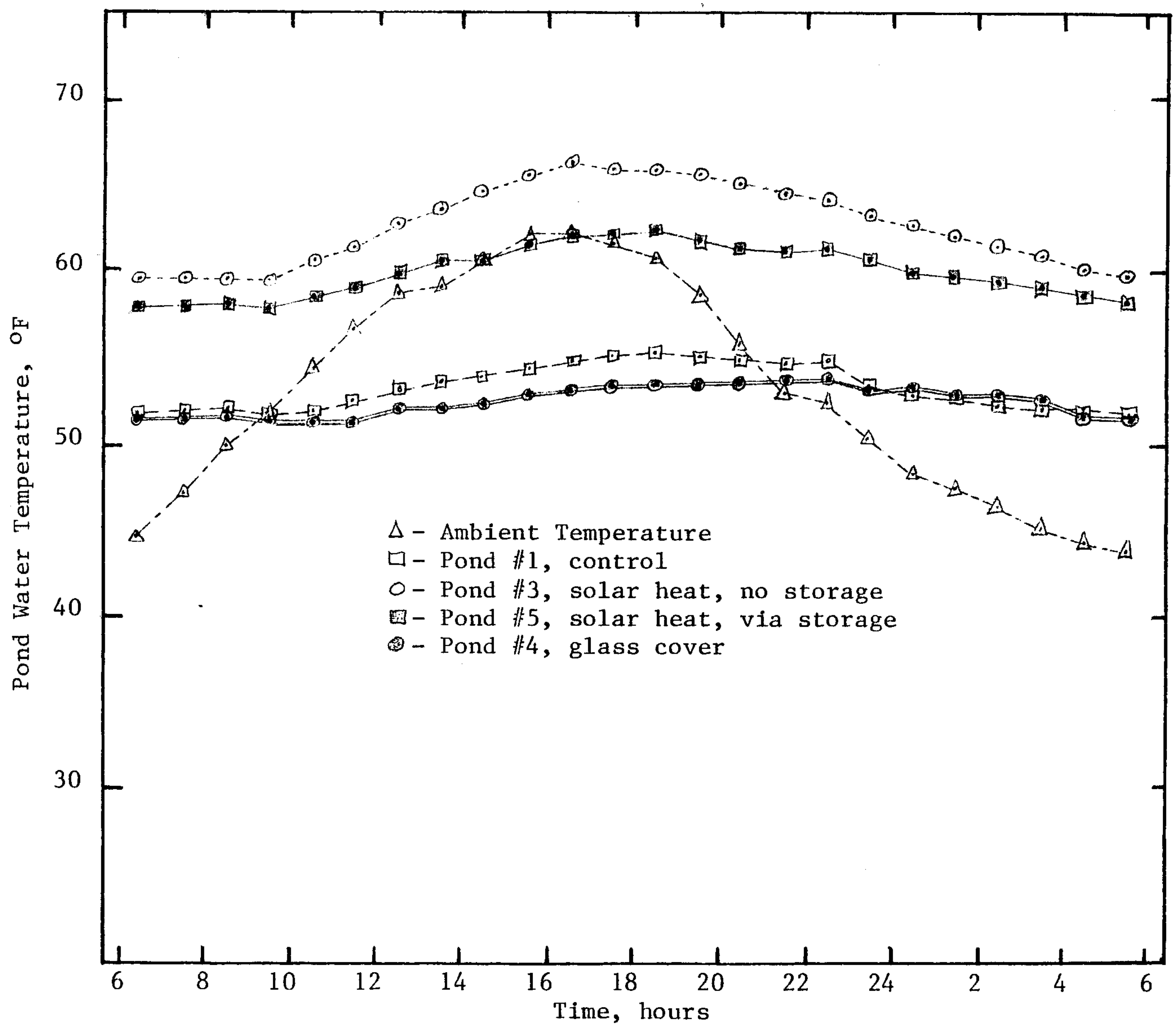

Figure A.2. Experimental Ponds: Average Daily Pond Water Temperature Cycle, May 1980–System Comparison

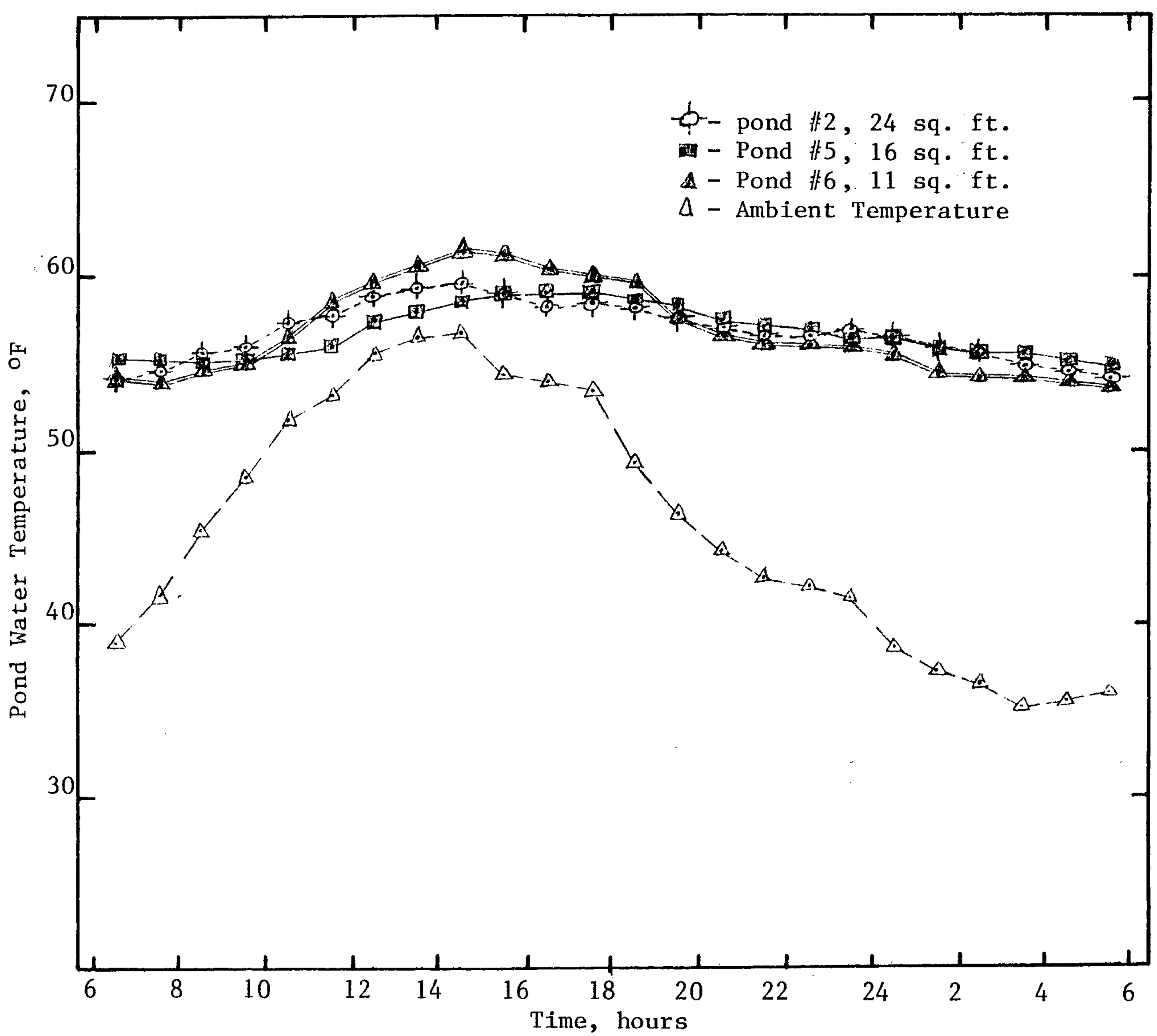

Figure A.3. Experimental Ponds: Average Daily Pond Water Temperature Cycles for Different Sized Ponds, April, 1980

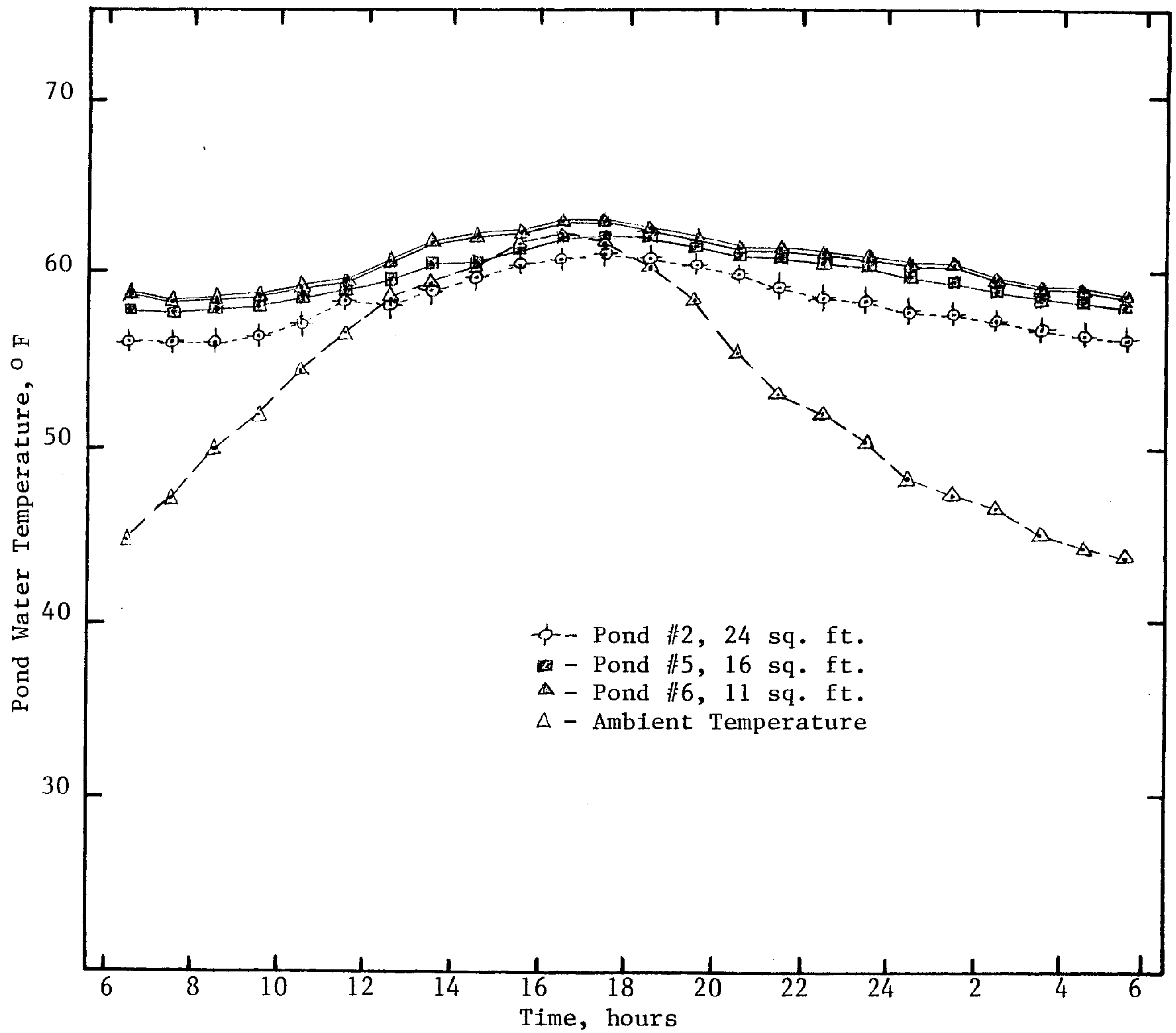

Figure A.4. Experimental Ponds: Average Daily Pond Water Temperature Cycles for Different Sized Ponds, May 1980

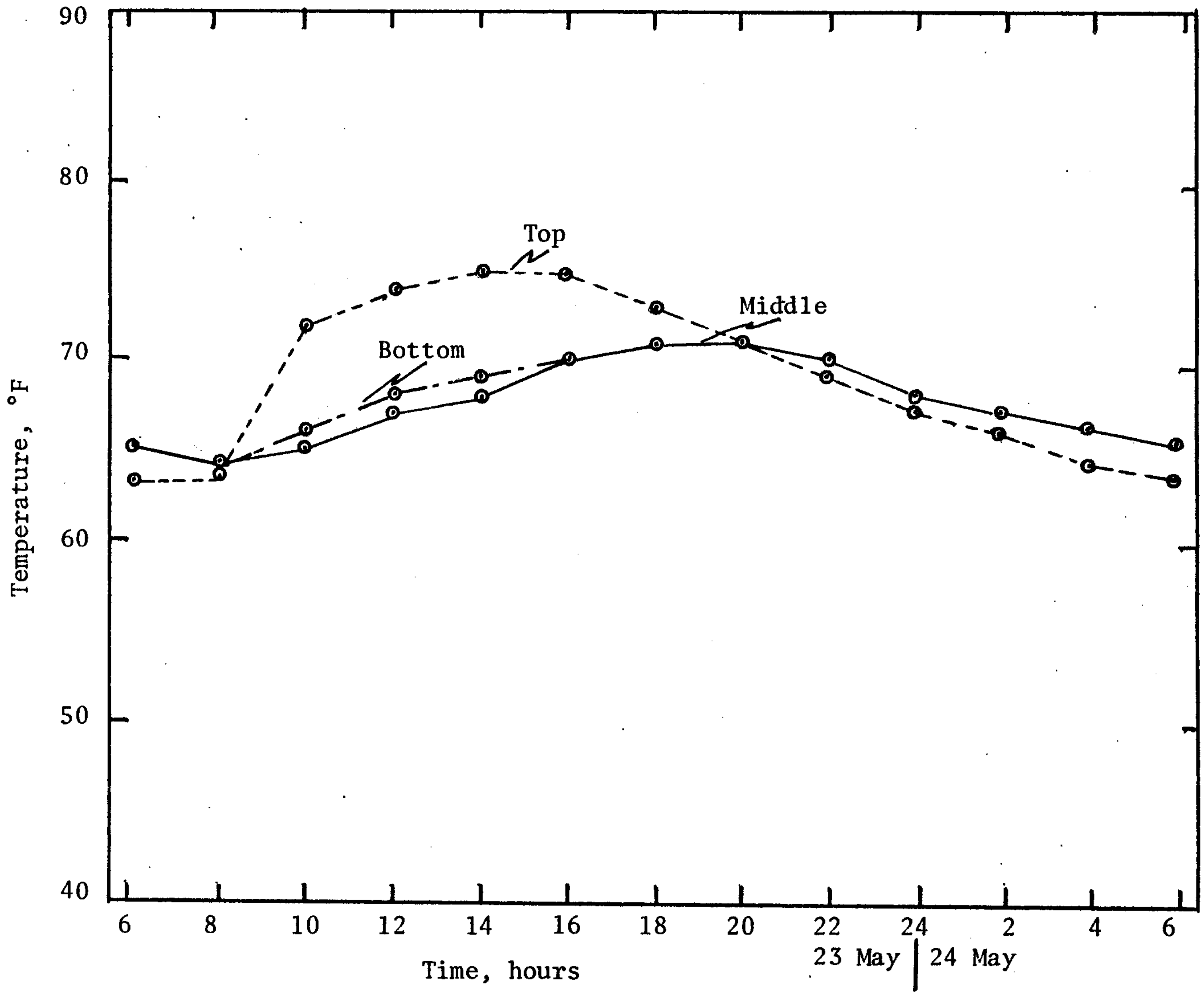

Figure A-10. Temperature Variations with Depth, Daily Cycle -- Pond No. 6, Solar Heat Added Via Storage, 11 Square Feet

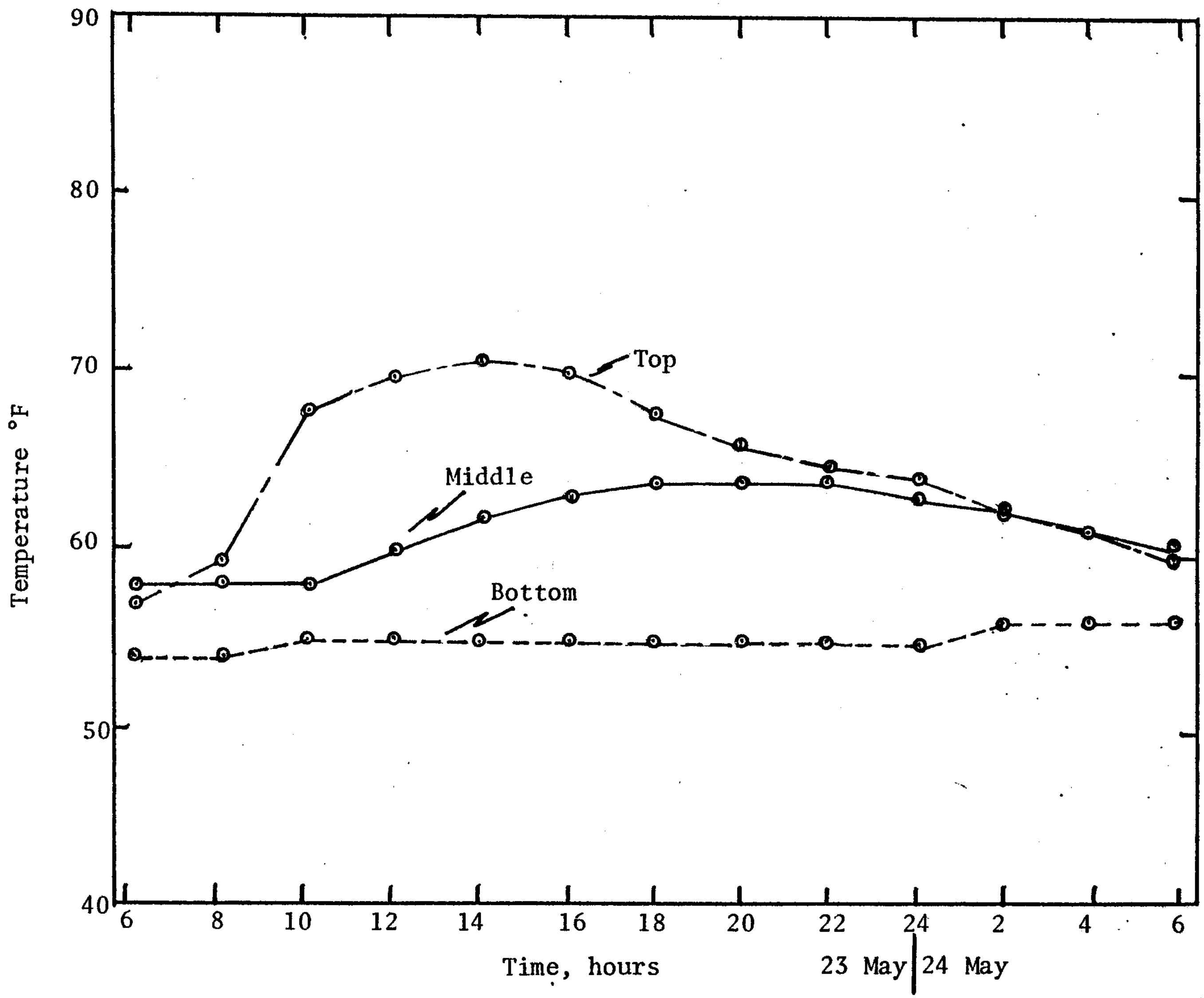

Figure A-5. Temperature Variations with Depth, Daily Cycle -- Pond No. 1, Control, 16 square feet

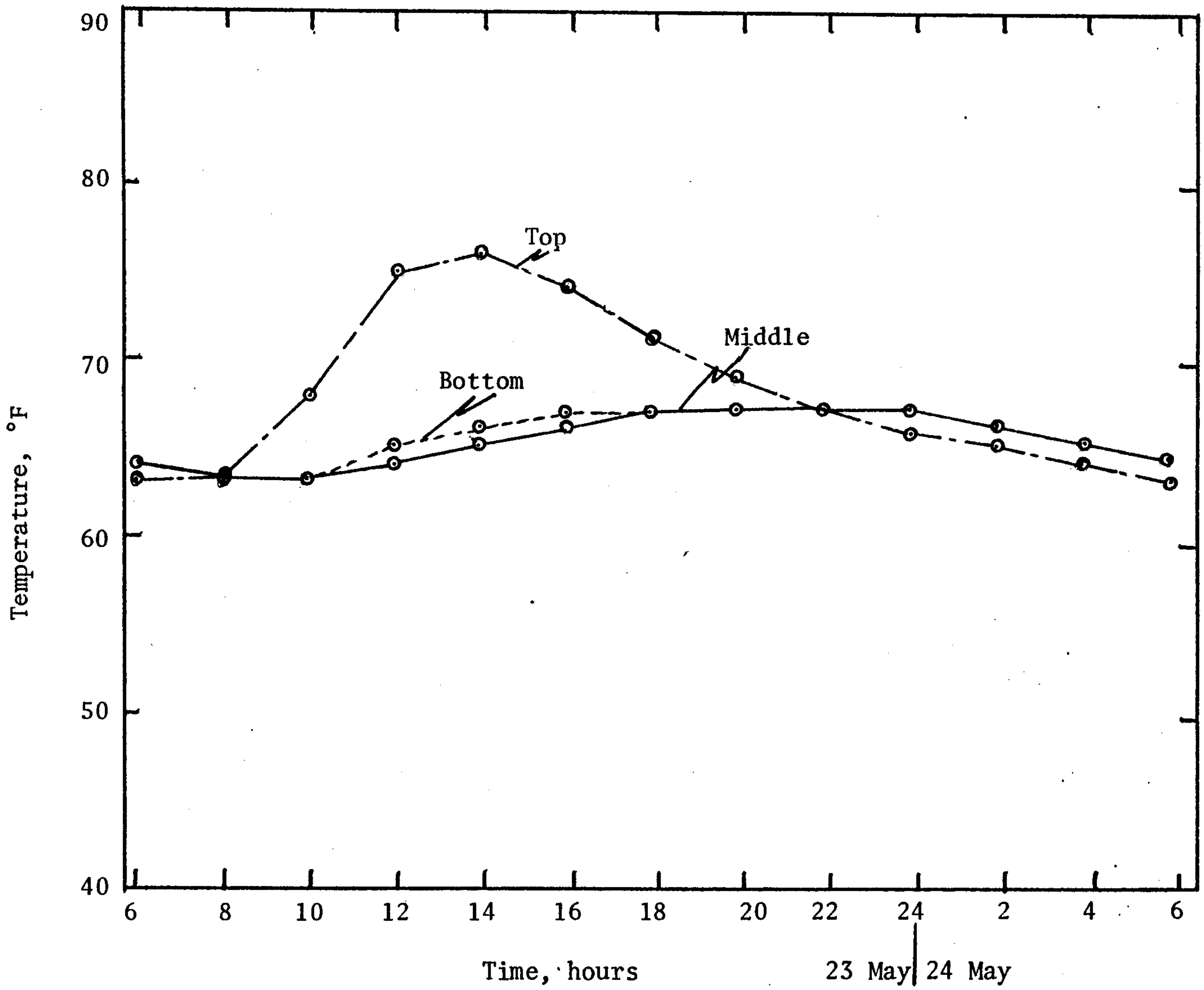

Figure A-6. Temperature Variations with Depth, Daily Cycle -- Pond No. 2, Solar Heat Added Via Storage, 24 Square Feet

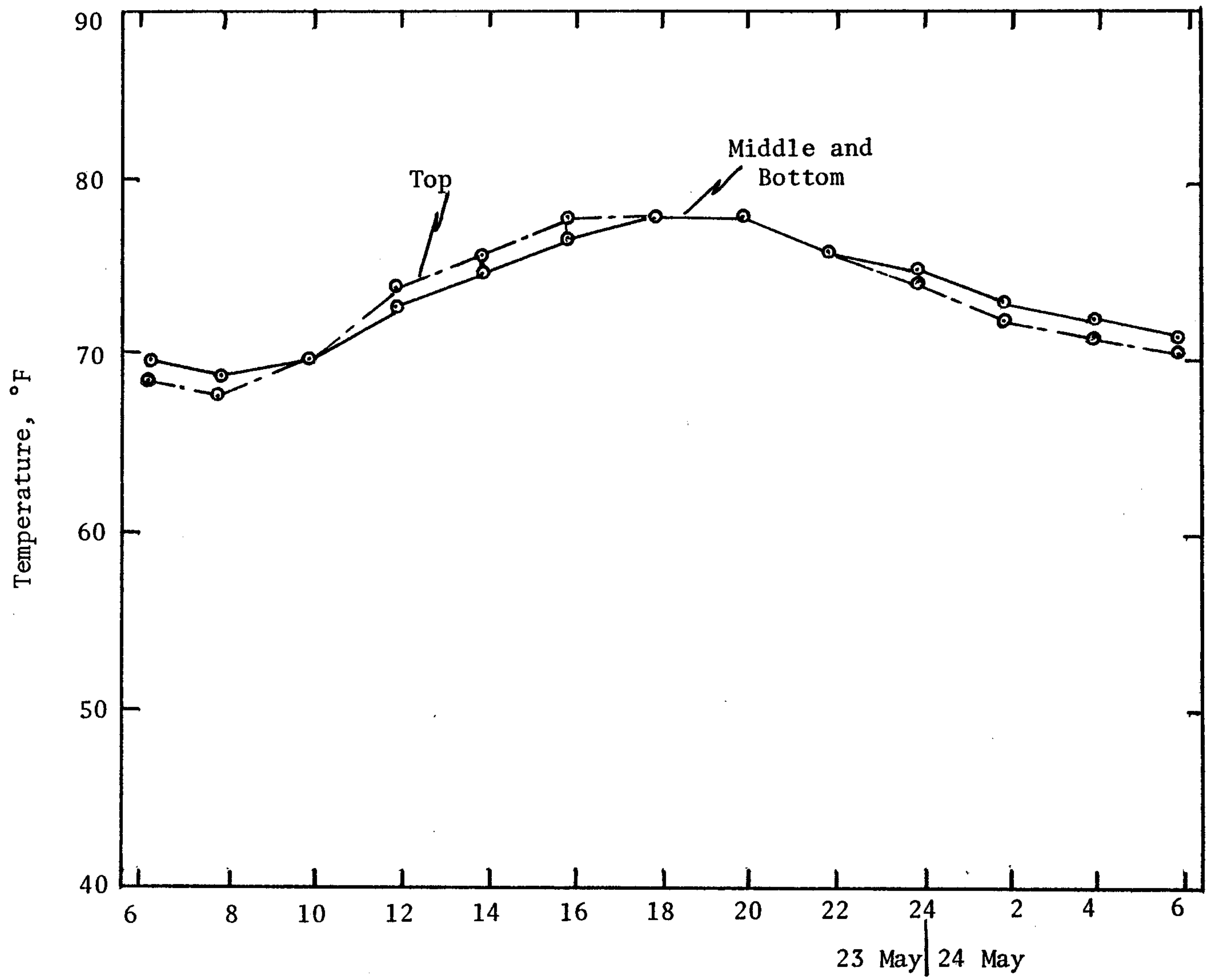

Figure A.7 Temperature Variations with Depth, Daily Cycle -- Pond No. 3, Solar Heat Added Directly, No Heat Storage, 16 Square Feet

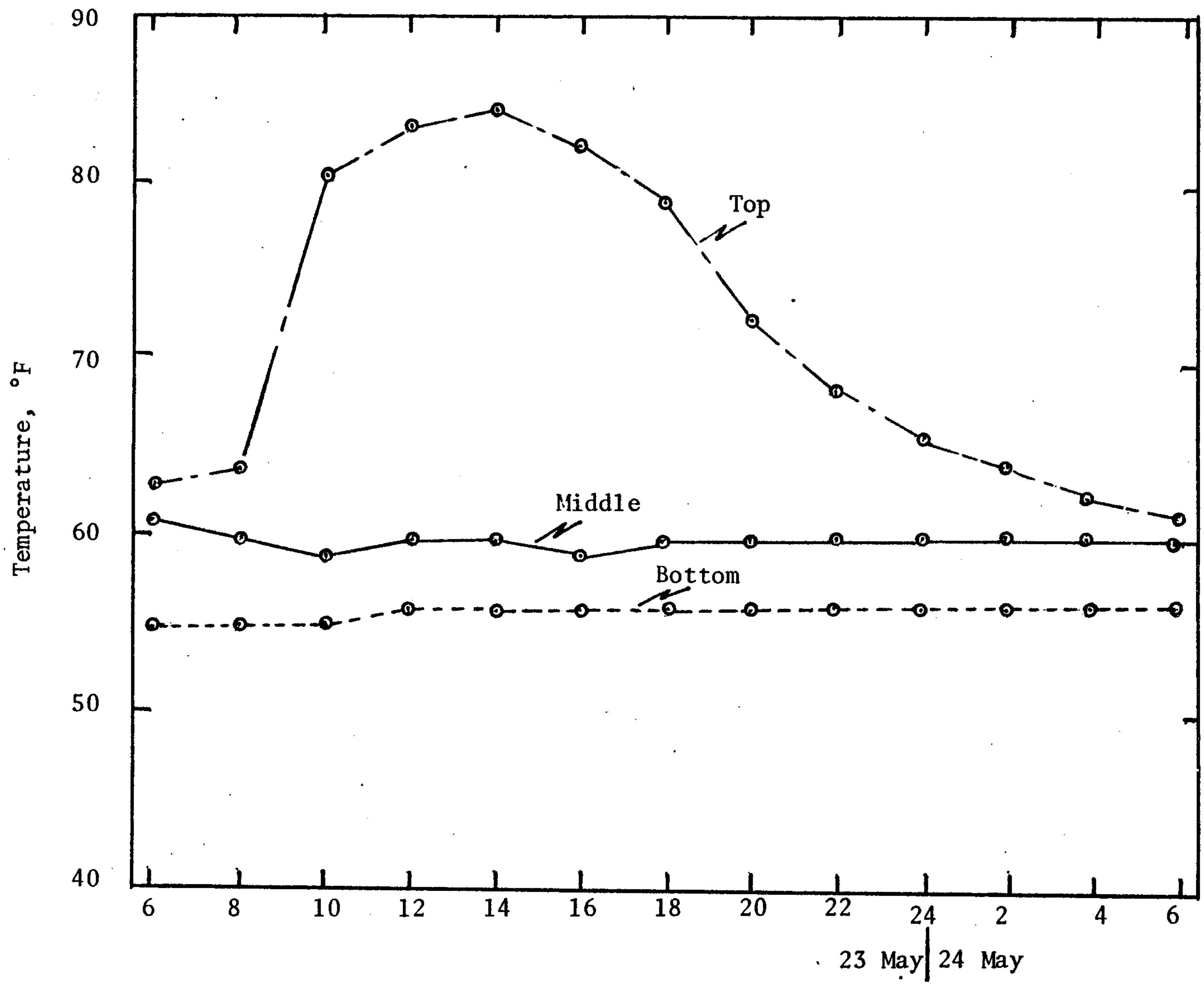

Figure A-8. Temperature Variations with Depth, Daily Cycle -- Pond No. 4
Glass Cover, 16 Square Feet

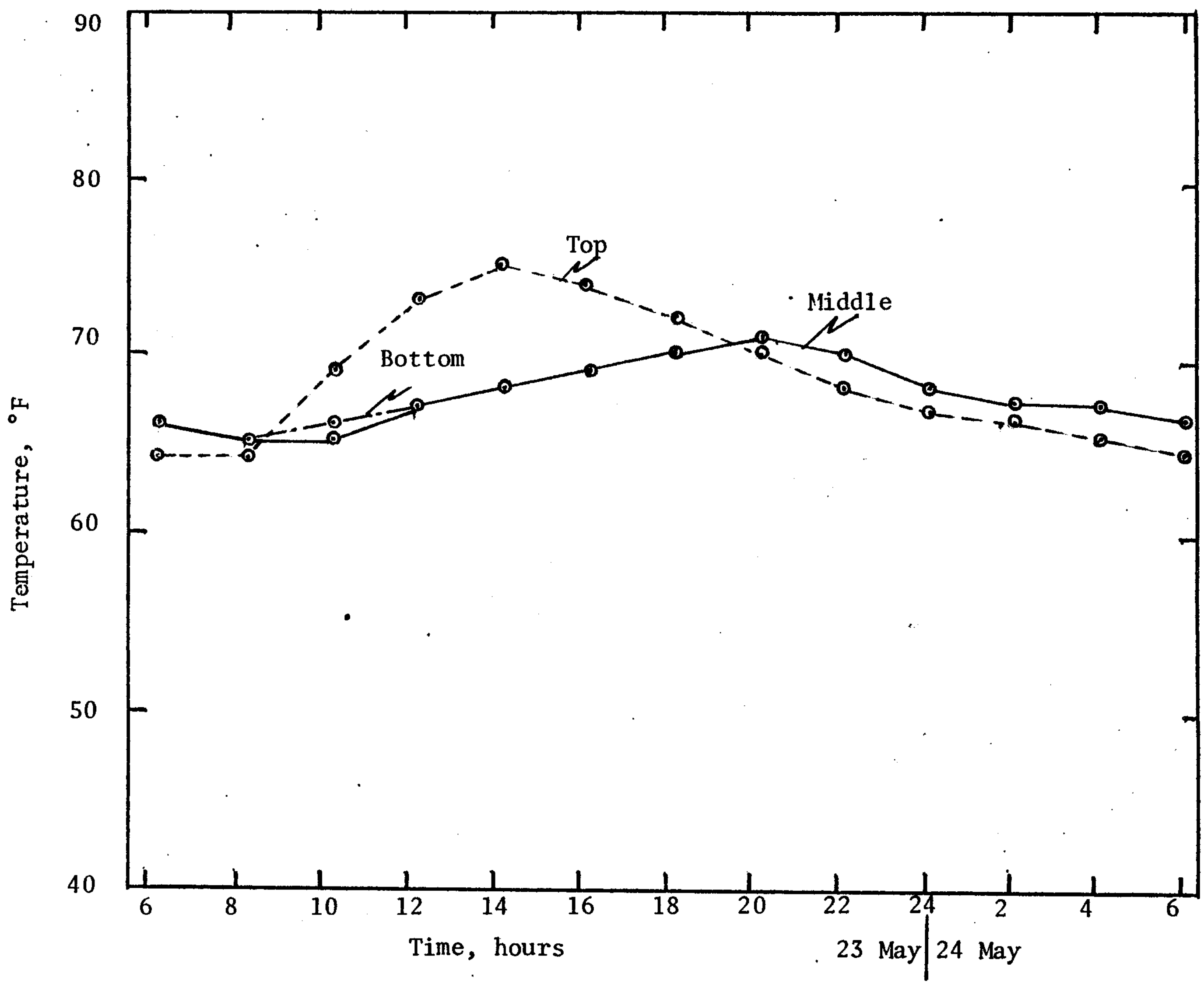

Figure A-9. Temperature Variations with Depth, Daily Cycle -- Pond No. 5, Solar Heat Added Via Storage, 16 Square Feet

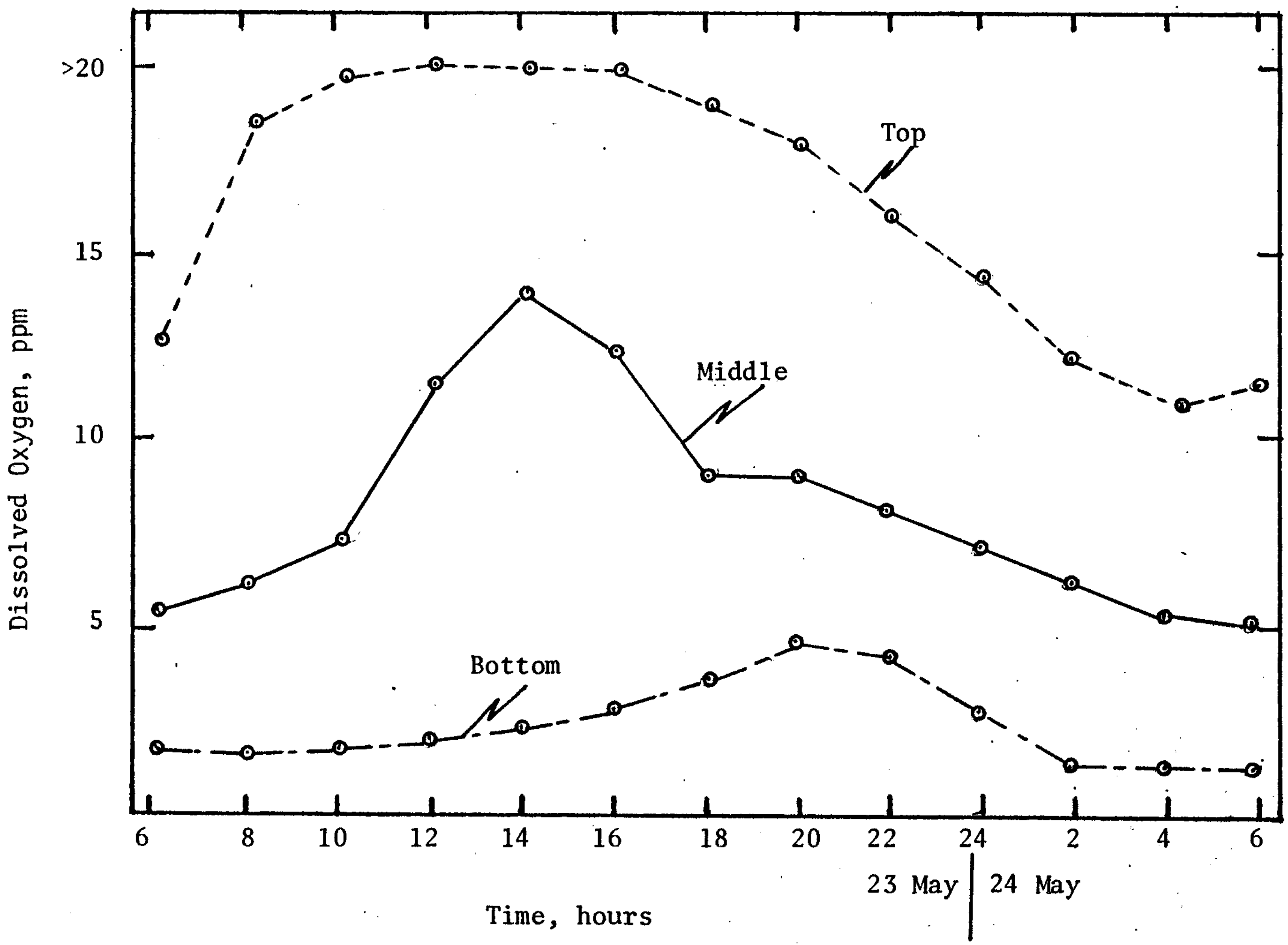

Figure A-11. DO Variation with Depth, Daily Cycle -- Pond No. 1

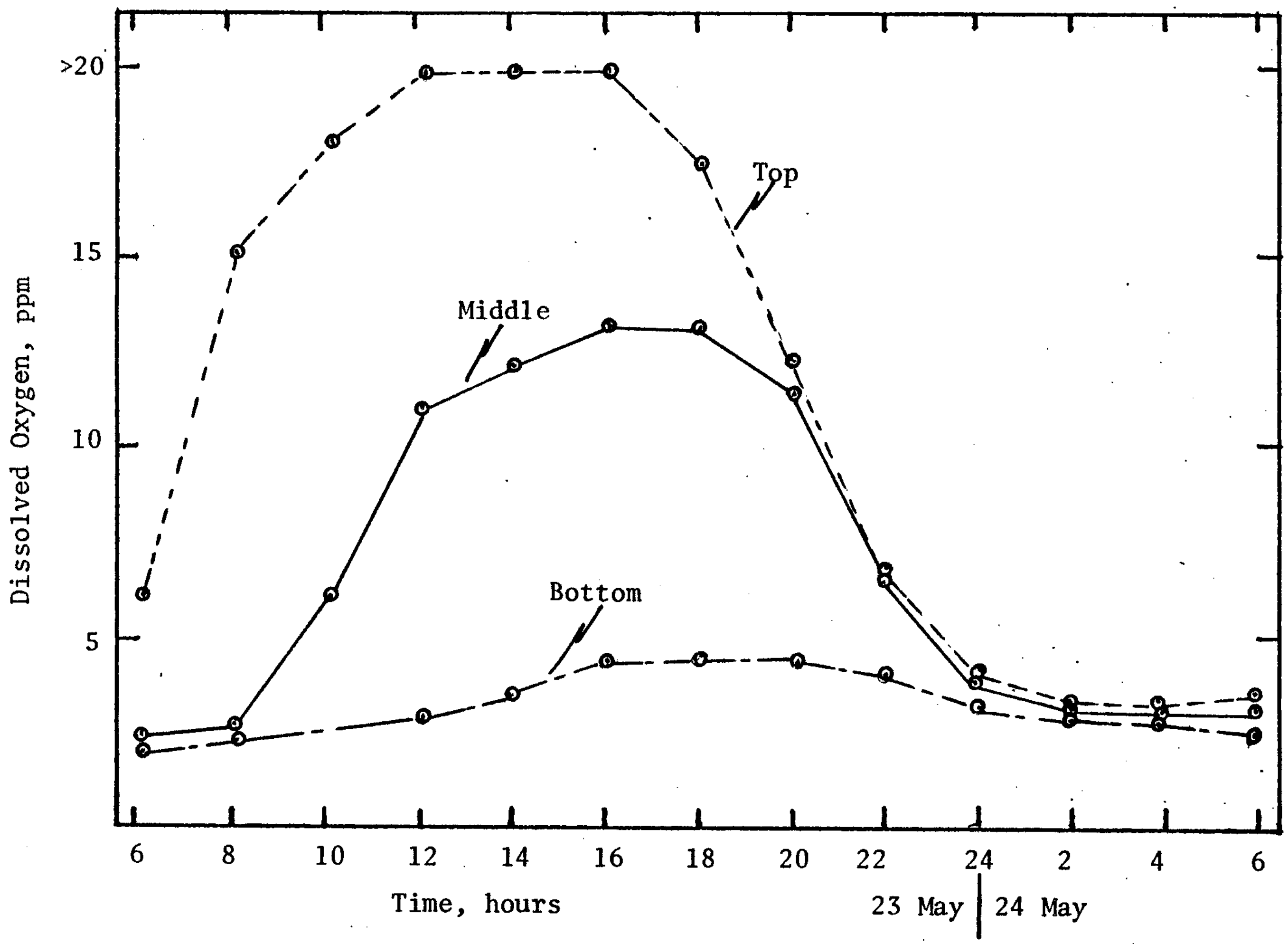

Figure A-12. DO Variation with Depth, Daily Cycle -- Pond No. 2

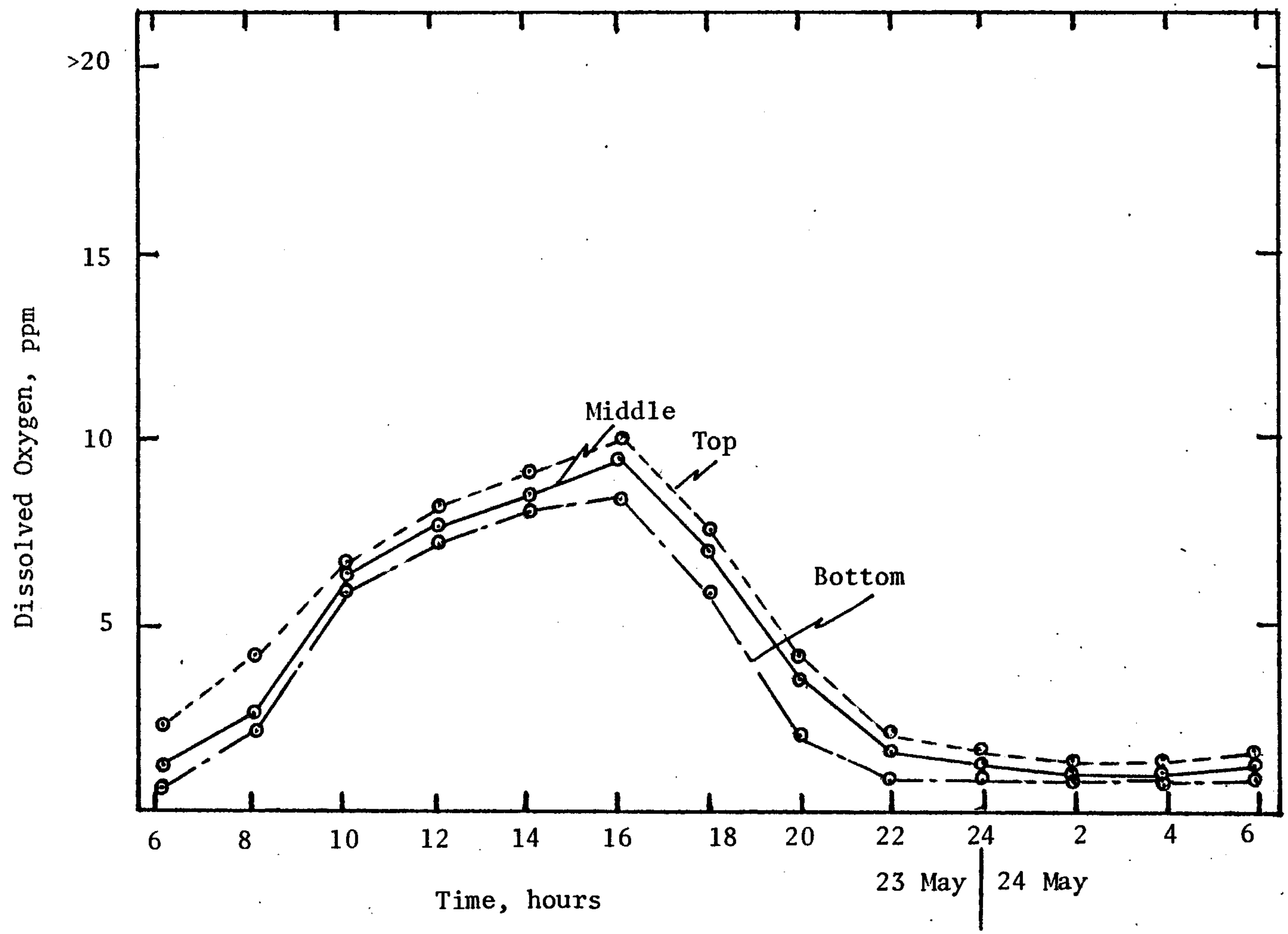

Figure A-13. DO Variation with Depth, Daily Cycle -- Pond No. 3

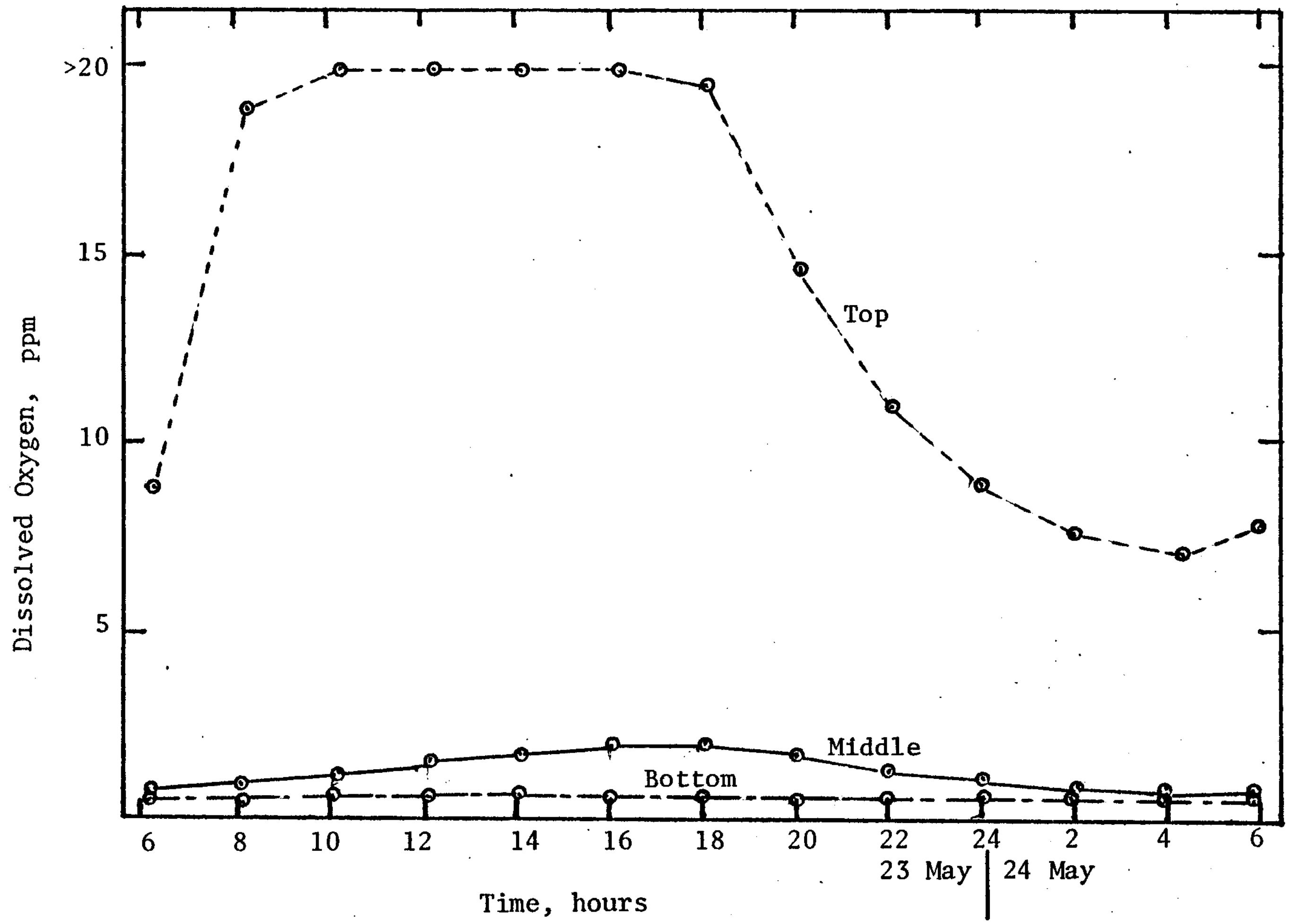

Figure A-14. DO Variation with Depth, Daily Cycle -- Pond No. 4

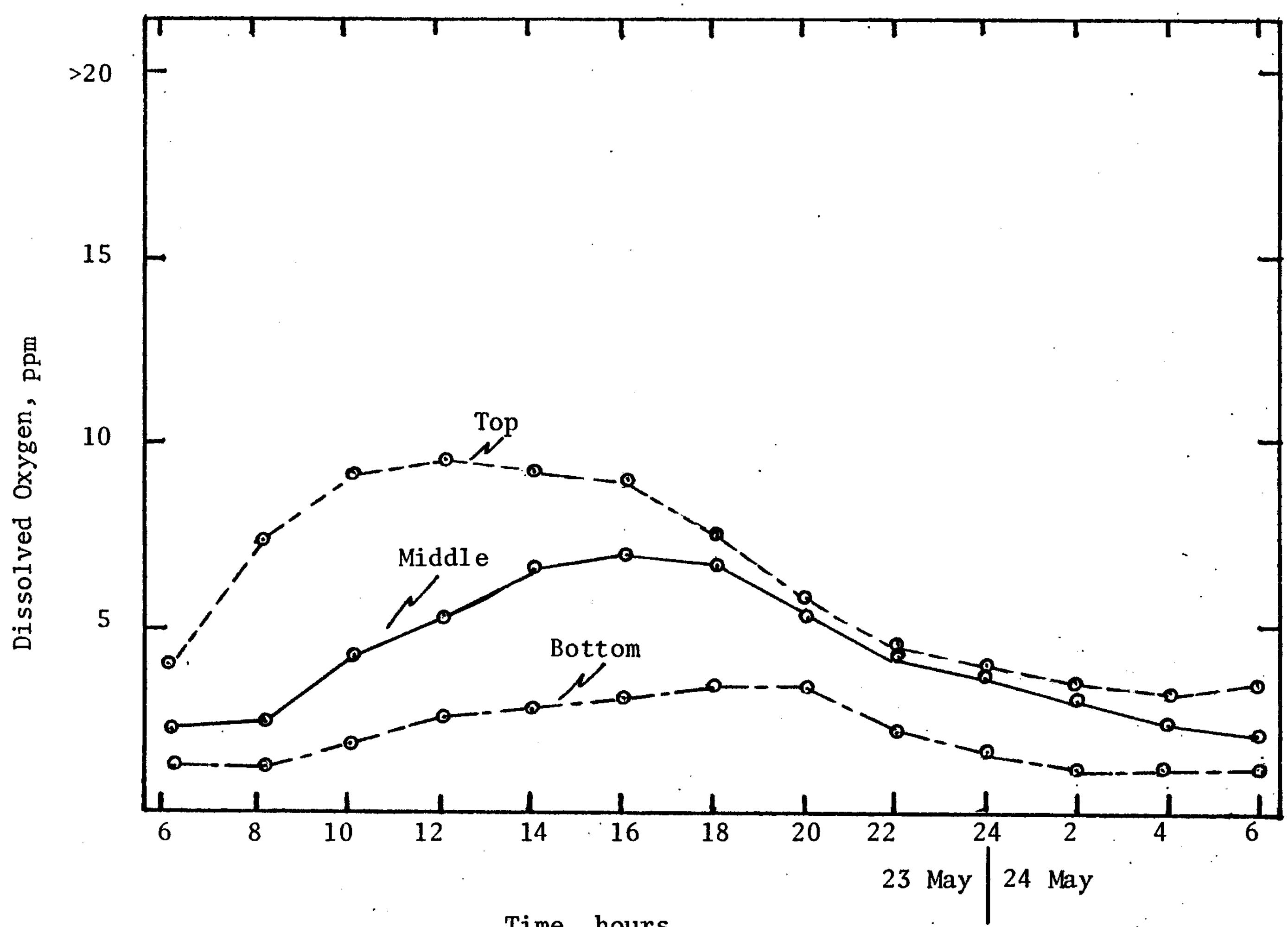

Figure A-15. DO Variation with Depth, Daily Cycle -- Pond No. 5

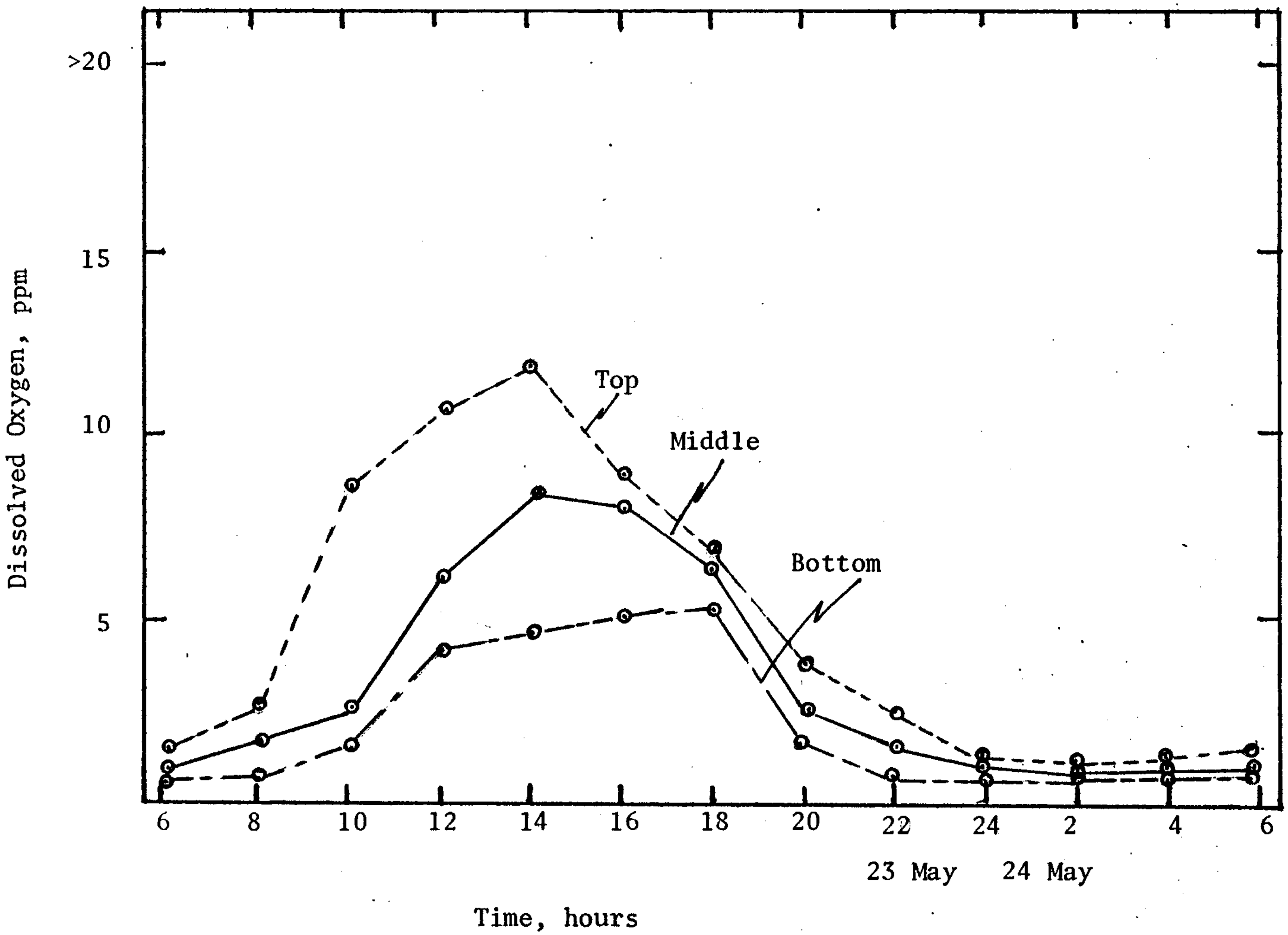

Figure A-16. DO Variation with Depth, Daily Cycle -- Pond No. 6

Table A-1. Average Pond Water Temperatures

Time Period	Pond Number					
	No. 1	No. 2	No. 3	No. 4	No. 5**	No. 6**
April	46.8	51.2	54.3	44.3	56.7	56.8
ΔT*		4.4	7.5	-2.5	--	--
May	53.3	58.2	62.5	52.6	59.8	60.4
ΔT*		4.9	9.2	-0.7	6.5	7.1
Overall	50.5	55.2	59.0	48.9	59.1	59.4
ΔT*		4.7	8.5	-1.6	--	--

*ΔT = Temperature of the Pond minus Temperature of the Control Pond No. 1

**Ponds No. 5 and No. 6 were not operational the first half of April, therefore, their April and overall values are not compared to the other ponds.

Table A-2. Biochemical Oxygen Demand, mg/l -- Test Results

Date	Pond Number					
	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6
April 28, 80	30	32	21	38	27	28
April 30, 80	36	62	28	50	22	47
May 2, 80	24	25	19	34	45	39
May 4, 80	31	29	22	40	29	26
May 8, 80	19	24	13	30	25	33
May 12, 80	23	24	15	34	16	37
May 16, 80	15	23	28	60	90	--
May 20, 80	34	41	15	35	40	75
May 24, 80	35	48	15	43	13	18
May 26, 80	28	18	18	30	15	18
May 28, 80	53	43	40	56	35	31
May 30, 80	80	53	50	55	43	83

APPENDIX B

COMPUTER MODEL RESULTS

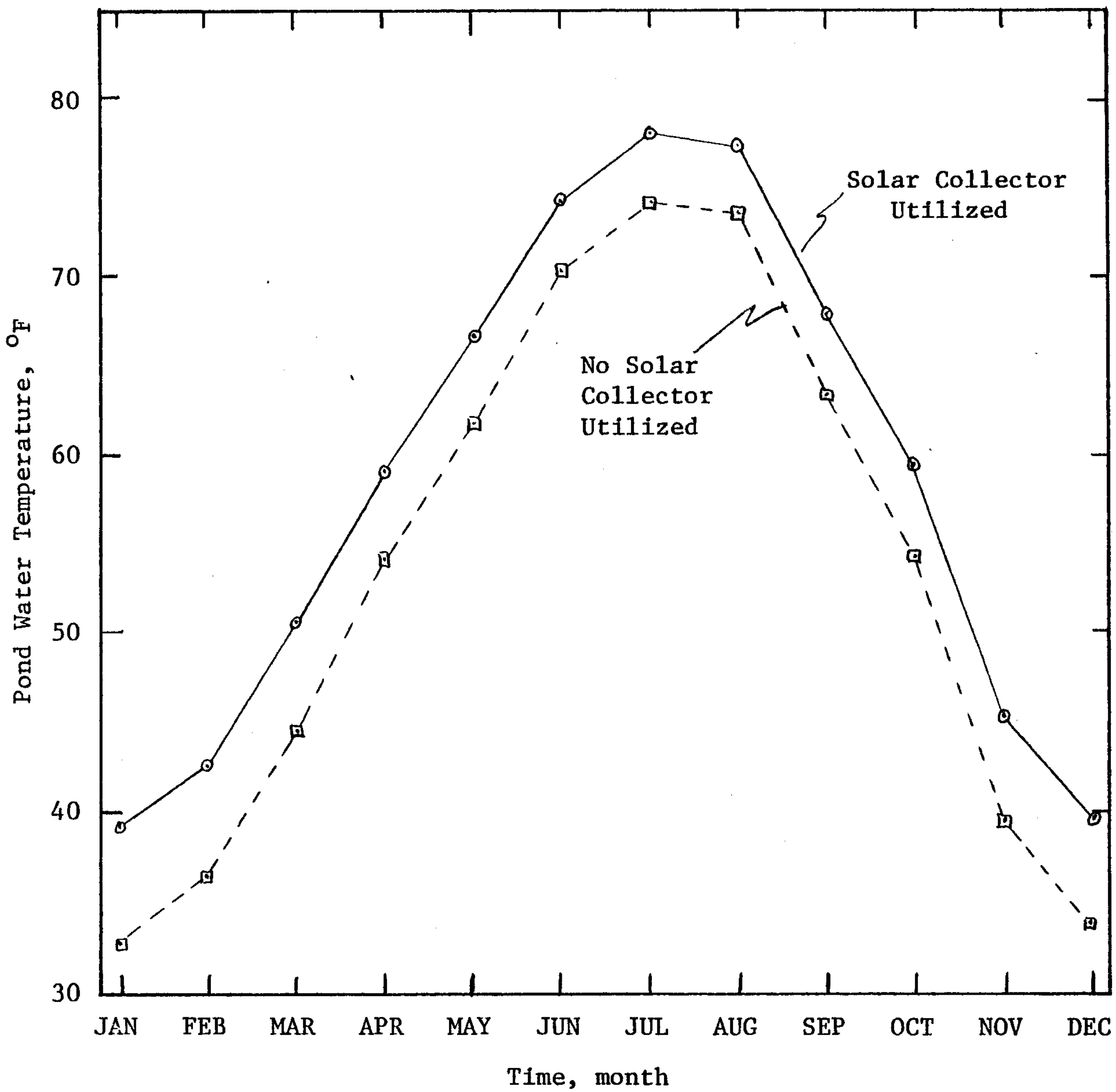

Figure B-1. Computer Model Pond Water Temperature Analysis; Solar Collector Utilized vs. Natural Pond -- Yearly Cycle

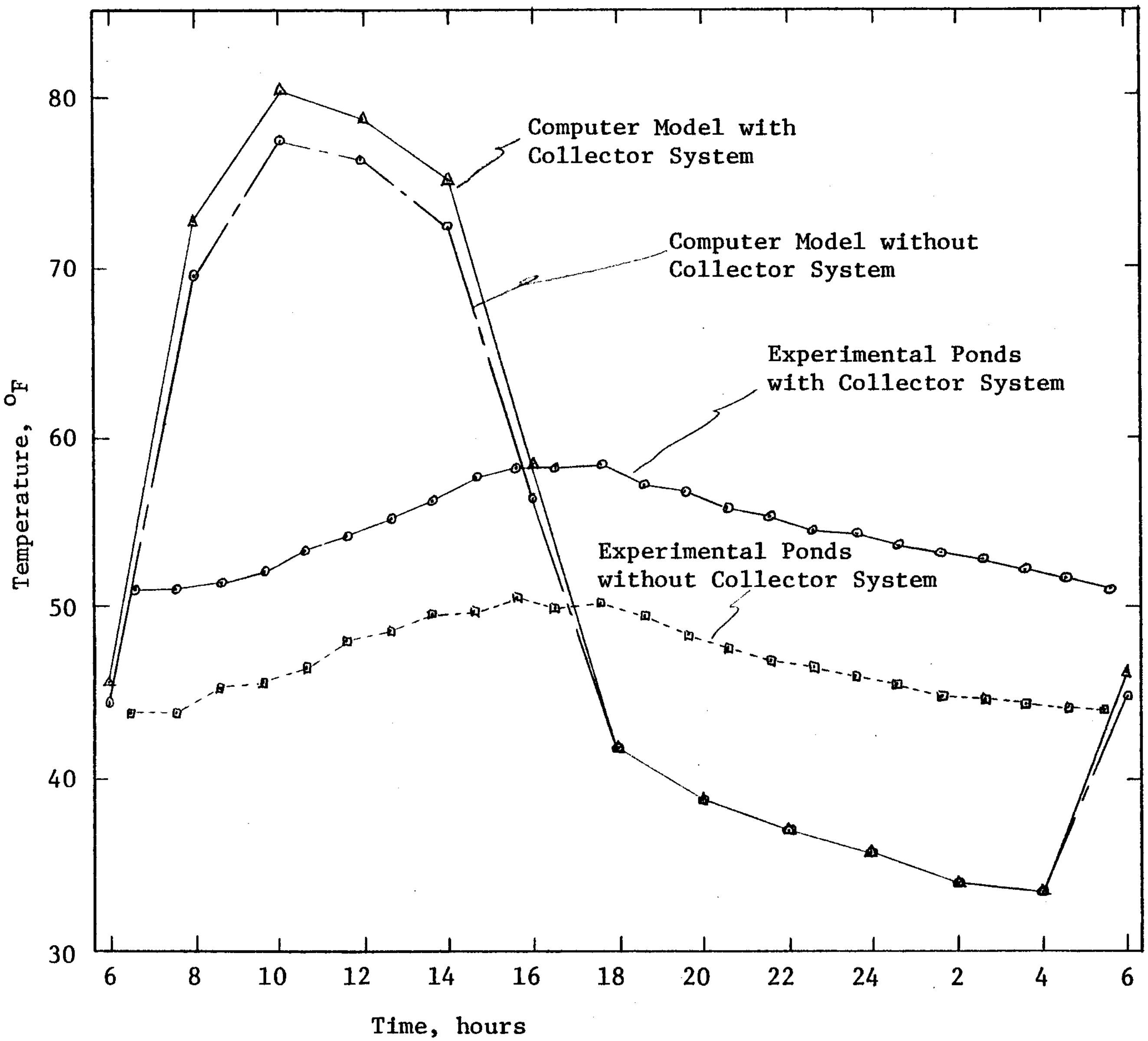

Figure B-2. Pond Water Temperature Comparisons; Computer Model Results vs. Experimental Ponds -- Daily Cycle, April

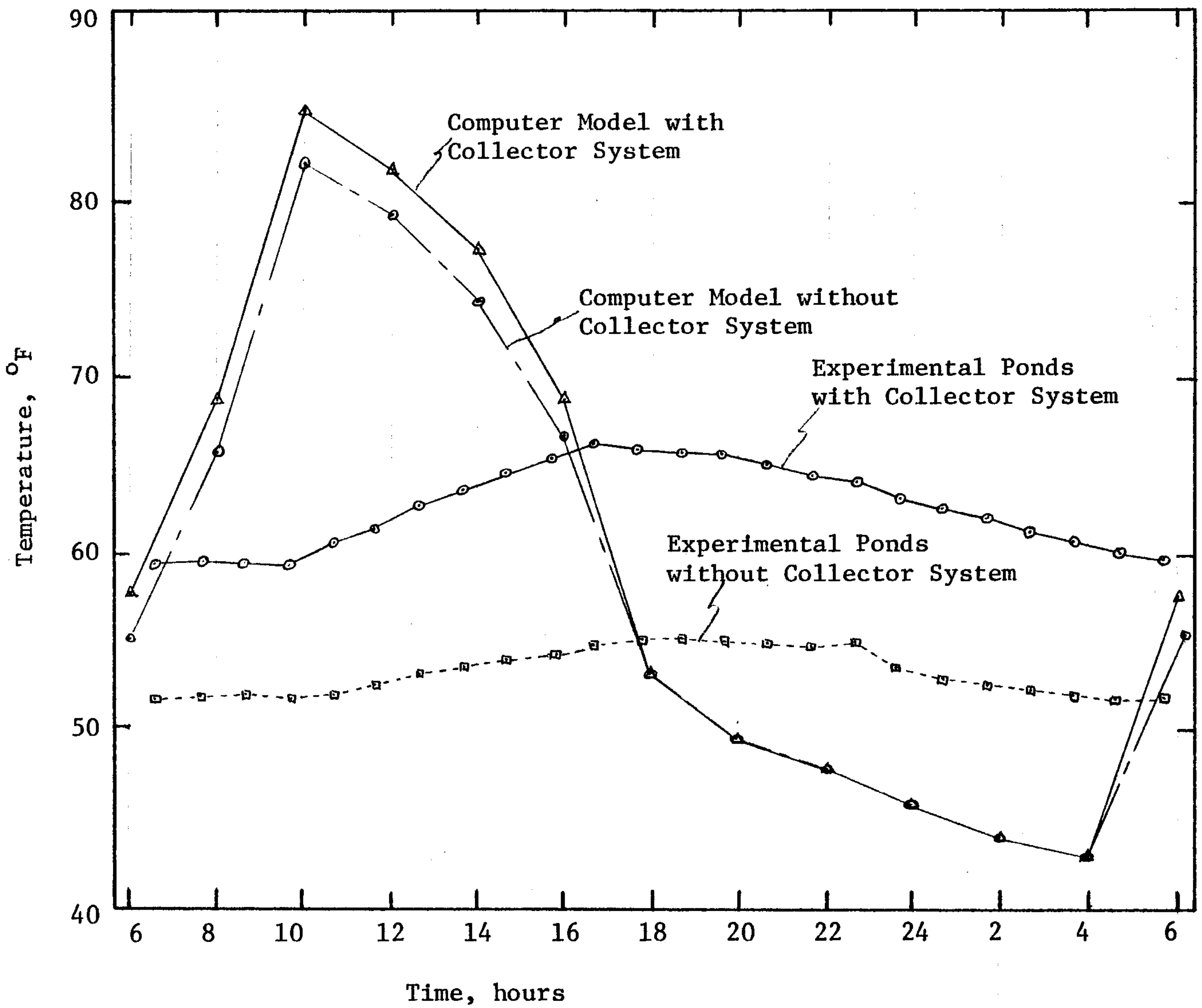

Figure B-3. Pond Water Temperature Comparisons; Computer Model Results vs. Experimental Ponds -- Daily Cycle, May

Table B-1. Area (sq. ft.) Maintained At A Given Pond Water Temperature - Collector Size = 16 sq. ft.

Month		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Ambient Air Temperature, °F		26.8	30.7	35.4	46.4	55.6	64.3	70.8	68.9	60.0	49.6	37.2	30.3
Water Temperature °F	33	719.01	**	**	**	**	**	**	**	**	**	**	**
	35	73.11	**	**	**	**	**	**	**	**	**	**	132.15
	40	20.8	44.02	**	**	**	**	**	**	**	**	368.75	21.21
	45	11.27	17.42	367.79	**	**	**	**	**	**	**	22.62	10.56
	50	7.28	10.12	32.67	**	**	**	**	**	**	**	10.57	6.57
	55	5.1	6.73	15.7	170.24	**	**	**	**	**	204.4	6.39	4.49
	60	3.74	4.78	9.68	23.45	**	**	**	**	**	23.06	4.28	3.22
	65	2.82	3.52	6.62	11.42	42.73	**	**	**	82.64	11.08	3.03	2.38

** - Infinite sized area will be supported at this temperature.