A METHOD FOR IMPROVING PERFORMANCE OF COOLING PONDS

A Thesis

Presented to

the Faculty of the Department of Civil Engineering

The University of Houston

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

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Charles M. Wilcox

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ABSTRACT

This thesis presents the results of a study of the efficiency of a cooling pond as related to temperature decreases, residence times and flow patterns.

A literature review of cooling pond design principles and operational experiences was undertaken to more accurately relate the theoretical performance relationship of model and prototype.

Laboratory experiments were conducted using a model of distorted scale with a flexible simulated levee system. Flow patterns and temperature decreases are correlated with various levee arrangements and the efficiency of the overall system is defined. The pond's capability as a wastewater treatment facility is also discussed.

Conclusions are made on the effect of various factors influencing performance and overall efficiency of cooling ponds. Recommendations for further study of parameters relating to cooling pond design are also made.

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CHAPTER I

INTRODUCTION

Water has become a vital resource in the process of cooling as related to many industrial operations. The use of water will probably increase dramatically in the very near future; a prognosis that becomes easily substantiated when one considers the anticipated growth of the electric power industry, a major user of water as a cooling medium.

With increasing population one can predict a trend increase in the demand for electric power. Based on previous years, this demand will double each decade until 1990 when the total installed power capacity in the United States will approach 1,200,000 megawatts (1). This increase in total capacity will, in the interest of economy, precipitate a corresponding increase in the size of the generating units so that by the year 1990 a 2000 megawatt unit will not be uncommon. The limited availability of suitable hydroelectric sites establishes the requirement for a corresponding growth in the number of steam electric stations since other sources of power generation cannot economically account for a substantial portion of the predicted power requirements.

A standard procedure in many industries is to take water from a source, pass it through the cooling process, which is normally self contained in a closed system so there is little consumptive use of the water, and then discharge the heated effluent back to the source of supply. These discharges may well contribute to changes in the physical and biological characteristics of the receiving body through calefaction; these changes may be proven beneficial, detrimental or, at least insignificant. The actual effect of these changes are variable and dependent upon the ecology of the receiving body and its use. However, because of the unknown, yet feared, potential synergistic impact this waste heat may have on the quality of the receiving body, a critical problem facing industry today is its proper control and dispersion within the environment.

Some of the techniques utilized in controlling the temperature of cooling water discharges are cooling towers and spray ponds. While both of these methods are efficient in the matter of temperature change, they each have two inherent economic disadvantages, namely high initial cost and recurring maintenance and operating costs. To be considered also are their aesthetic qualities and their associated mist and fogging infirmities; a severe problem in areas where brackish water is used for cooling. One method of controlling discharge temperatures which does not share these same disadvantages is that of a flow through cooling pond. This method is a particular benefit in areas where brackish water is used for cooling purposes or where recirculation of cooling water is technologically beneficial.

This research project was initiated and conducted as a four-fold approach to the question of cooling pond performance. First it presents the results of knowledge gained on the performance of a cooling pond as a thermal control mechanism. Secondly, through model tests, it describes methods which may be utilized to increase the performance and efficiency of a prototype full scale pond. Thirdly, through evaluation of flow patterns and velocity distributions within a pond's system, procedures are suggested that will lead to the detection of non-functional areas of the pond so that they may be utilized or eliminated. Fourth, but of lesser importance, it defines the wastewater assimilative capacity of a pond as related to its flow and residence time.

CHAPTER II

LITERATURE RESEARCH

GENERAL

The art of evaluating the potential of a site's environment to absorb vast quantities of waste heat from a thermal process industry is limited in the light of today's technology. The growth of these industries and the attendant increase in plant size and circulating water requirements has resulted in a limited availability of sites where cooling water supply is adequate to meet both the demands of industry and thermal criteria of water quality agencies. Recently, there has been growing interest in the use of cooling ponds as a means of satisfying the thermal criteria limitation of water demands. Depending on the availability of land, these devices offer a cheap and effective mechanism for heat rejection.

Cooling ponds are highlighted by some of their characteristic advantages. To name but a few; carry over of nighttime low temperature into the day period, coupled with this, is their function as a heat sink for absorbing higher temperature influents. Additionally, they provide greater evaporative cooling through greater air/water interface area. Of lesser importance is their recreational adaptability and waste treatment capability. As compared to their advantages, they need not be elaborate systems but simply a man-made or natural depression with an impervious lining (2). As an overall evaluation, cooling ponds are less expensive than the more thermally efficient cooling towers when such factors as initial cost, operating expenses, maintenance cost and long life probability are considered (3).

Generally speaking, cooling ponds can be classified as three types; 1) completely mixed ponds, 2) flow through ponds, and 3) internal circulating ponds. This classification is made on the basis of two broad factors; circulation pattern and temperature distribution. The actual characteristic circulation to be expected in any pond depends primarily upon its geometry, location of plant intake and discharge points, effects of wind and plant pumpage rate (4).

DESCRIPTION OF HEAT EXCHANGE MECHANISMS

In evaluating the temperature and heat capacity of a body of water as a function of time, certain factors governing the rate of heat gain or loss must be considered. These are: (5)

1) Solar radiation incident to the water surface
2) Reflected solar radiation
3) Long-wave radiation between the body of water and the atmosphere
4) Sensible heat conducted from the water to the atmosphere
5) Evaporation at the water surface
6) Long wave back radiation

Basically, these heat transfer relationships could be broadly reclassified as three major mechanisms; radiation, evaporation and conduction. Figure II-1 shows a pictorial version of this heat or energy spectrum and its contributory factors. The extent to which these mechanisms play a part in the overall heat budget of a system depends on basic meteorological factors such as radiant energy from the sun and atmosphere, air temperature and absolute air humidity and the wind velocity and its turbulence (6). In formulating an understanding of the principles of atmospheric heat transfer, it would be beneficial to briefly discuss the relationship of each of the three mechanisms; the intent being not to delve into the mathematics of heat transfer, but rather offer a concise presentation of the related theories. Where, in definition, equation format is presented, symbols are defined in Appendix A. Unit conformity of the following equations is maintained through the constants specified in each equation. For additional information on the derivation of each equation and unit compatibility, the reader is referred to Appendix E for summary of the original reference sources for a detailed presentation.

Heat transfer by radiation represents the combined effects of solar radiation, long-wave atmospheric radiation and back radiation. Each of these are closely related and affected by many of the same factors such as cloud cover, vapor pressure and, in the case of solar radiation, latitude (5), (7). For example, on cloudy days heat input by solar radiation

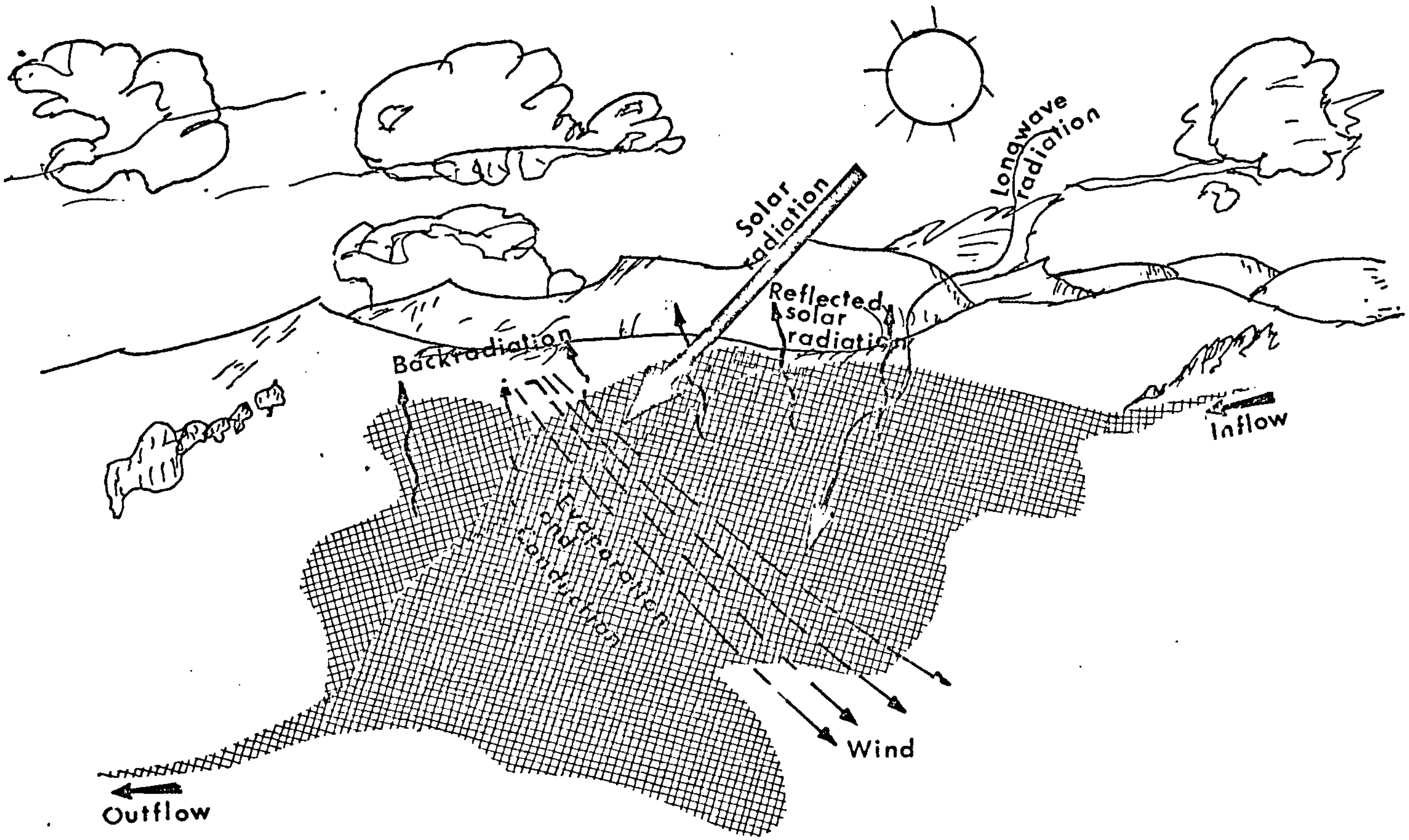


FIGURE II-1
FACTORS AFFECTING HEAT TRANSFER

may be low and consequently long-wave atmospheric radiation may constitute the major portion. The amount of heat received through each of these primary radiation factors may be estimated by computation using empirical relationships. These should be considered since significant errors would be introduced if proper allowance were not made for them. The net solar radiation is a combination of measured and calculated terms. The following empirical formula has been developed for computation. Evaluation of the term "$Q_s - Q_r$" is possible through use of Figure I Appendix E. This curve represents the total effective incoming radiation plotted from measured values of actual solar radiation at varying solar incident angles (Figure 2 Appendix E) and corresponding reflected solar radiation values (5).

$$Q_i = (1-0.0071C^2)\ (Q_s - Q_r) \qquad (1)$$

Atmospheric radiation may be defined by (7):

$$Q_a = \sigma(T_6 + 460)^4 \beta \qquad (2)$$

Where β is an empirically derived constant used to define the atmospheric effects of cloud cover and vapor pressure (Figure 3, Appendix E). It represents the result of studies in correlating incoming radiation with easily observed ground level conditions such as vapor pressure, air temperature and estimated cloud cover. Back radiation is dependent upon dissolved solids and temperature and represents the amount of heat reflected from the atmosphere. It may be computed using (7)

$$Q_{br} = \gamma_w \sigma (Tw + 460)^4 \qquad (3)$$

Heat transfer through evaporation is perhaps more dependent on the meteorological conditions mentioned previously than either of the other two. This is founded on the fact that each pound of water that leaves a surface area as vapor carries with it its latent heat of evaporation; 1060 BTU. Consequently, evaporation is inversely proportional to absolute humidity (6) and directly related to windspeed for, without wind, it could only occur through molecular diffusion, a slow process unless a strong thermal gradient exists such that there is free convection. There is no method for measuring evaporation directly, but its rate and effect can be estimated through empirical computation utilizing (5):

$$Q_e = 12U\ (e_w - e_a) \qquad (4)$$

Heat transfer by conduction is sensible heat that is conducted to or from a water surface by air whenever a temperature differential exists between the two media (5). This heat transfer rate is approximately equal to the product of a transfer coefficient and the difference in temperature between the media. Conductive heat is a function of many variables and is related by both similarity and proportionality constants with the evaporative heat transfer (7). Heat loss through conduction may be defined mathematically as (5):

$$Q_c = 0.00407\ UP\ (Ta - Tw) \qquad (5)$$

As mentioned earlier, evaporative loss and conductive loss are similar and proportional.. This proportionality constant has been defined as Bowens ratio where (7);

$$B = Q_c/Q_e \tag{6}$$

In the development of a basic understanding of the mechanism of heat transfer it becomes necessary for the principles of surface phenomena described above to be combined to yield the total heat budget of the system (9). Symbolically:

$$\Delta Q = (Q_s + Q_a) - (Q_c + Q_e + Q_{br}) \tag{7}$$

In effect, the rate at which heat enters or leaves a body of water is determined by the sum of the rates heat is being exchanged by the three principal mechanisms. The actual temperature of a body of water exposed to meteorological conditions is continuously driven to an equilibrium temperature such that heat gain will balance heat loss. This heat transfer is directly proportional to the temperature differential. When there is no temperature differential there is no heat transfer and a condition of equilibrium is established (10). Theoretically an infinite time of exposure and surface area would be required to cool to an equilibrium condition.

Heretofore, we have been discussing heat exchange as a naturally occurring phenomenon. If heat is added artificially, as would be the case of a discharge of a heated effluent from a thermal process plant, another term, Q_p, would be introduced into our budget equation. Obviously, to determine the effect of this term on the natural heat balance, each of the terms in the budget equation must independently be analyzed. The definition of Q_p depends on inherent characteristics and efficiencies of the particular industry's operation. For example, for a steam electric generating station operation, the term Q_p would represent the station's gross heat input to the system for an average monthly period and would be determined as:

$$Q_p = L \times R\,(e_b - e_t)/A \qquad (8)$$

The resulting budget equation would then be defined as:

$$\Delta Q' = (Q_s + Q_a) - (Q_c + Q_e + Q_{br}) + Q_p \qquad (9)$$

Among the factors affected in a body of water through addition of artificial heat, Q_p, are the sensible heat loss, the back radiation rate and the forced evaporation rate (11). Since, by definition, heat has a direct relationship with temperature, corresponding changes in heat terms can predictively depict corresponding changes in temperature which can be used to corrolate with formats of discharge quality established by governing agencies.

APPLICATION OF HEAT EXCHANGE MECHANISMS TO PONDS

As mentioned previously, there are three classifications of cooling ponds; completely mixed, flow through and internal circulating. Of primary concern in this research will be the flow through pond since experimentation has been directed to the flow patterns within and temperature decrease along this type. Additionally, it is better suited for, and can act more conveniently as, a buffer between a thermal discharge and ambient receiving waters. Generally speaking, the basic temperature decay equation for the pond would be (4):

$$T_1 - T = (T_p - T)\, e^{-r} \qquad (10)$$

where:

$$r = KA/\rho C_w F_p \qquad (11)$$

When heat is added from some industrial source, this increases both the temperature of the water and the rate at which heat is lost. A new equilibrium temperature must be attained. This new temperature is a function of the increased rate of the three mechanisms of heat exchange from the water body to the atmosphere, radiation, evaporation and conduction. At any point within a pond corresponding to some time, the major processes considered to control the heat transfer mechanisms are:

1) The change of heat storage within that incremental water segment
2) The advection of heat downpond stimulated by the dynamic condition of a mean inflow velocity
3) The heat exchange rate capacity of the atmosphere, meteorological factors (10).

Even considering these controls the heat transfer function of the three mechanisms can be described and correlated with temperature. For example, dissipation of heat by conduction is directly proportional to temperature gradient and inversely related to vapor pressure gradients (11). Also, water heated above an equilibrium temperature tends to give off water vapor at a higher rate and saturate adjacent air layers rapidly. This explains why wind velocity has such a predominate effect on the evaporation formula, the higher the wind velocity, the faster dry air replaces saturated air and greater evaporative cooling occurs. Surface cooling of hot water through evaporation can set up convective circulation patterns within a pond and supplemental cooling is established (12). As water flows through a pond, cooling takes place largely by evaporation and to some extent by conduction and radiation (13). Actually, temperature decline is nearly logarithmic (Figure II-2) thus, while complete cooling cannot easily be obtained, it can be closely approached within reasonable limitation of time and area. Usually cooling to within 3°F or 4°F of equilibrium is considered a reasonable design limit for ponds (13).

In application of the principles described heretofore in estimating the performance of a cooling pond, it is first necessary to establish an equilibrium temperature estimate for the area. This can be accomplished using the parameters outlined in the previous section as applied to the natural heat budget equation. Apply to this heat values the heat load of the industry and, from the result, establish the pond outlet temperature.

Certain modes of heat transfer have been neglected in this summary presentation since their effect on the overall result is considered to be

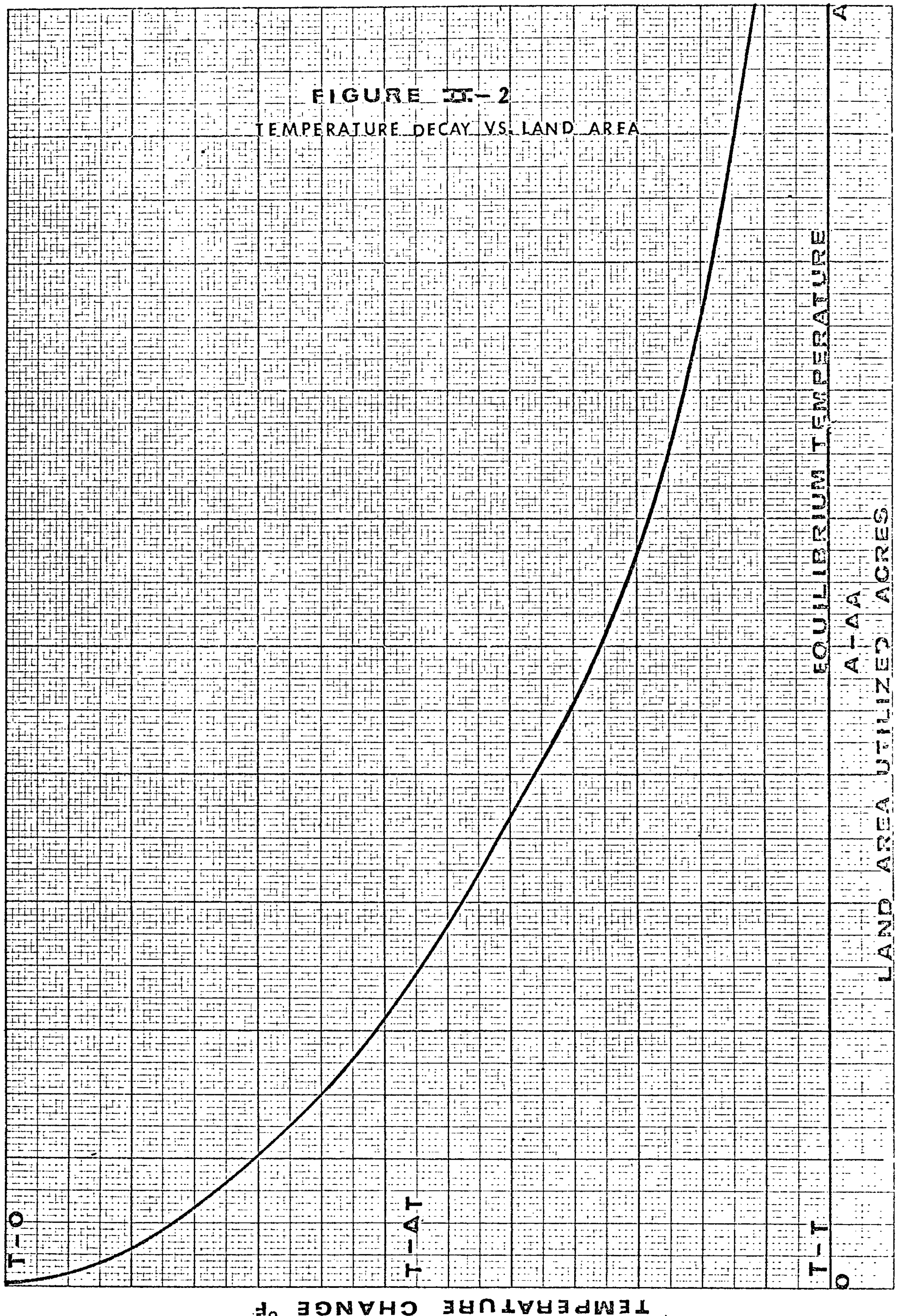


FIGURE II-2

TEMPERATURE DECAY VS. LAND AREA

negligible. Such factors include chemical and biological processes, conduction of heat from within the earth and short wave radiation which is not grossly absorbed in relatively shallow ponds studied in this project.

PHYSICAL FACTORS AFFECTING COOLING POND EFFICIENCY

The theoretical formulae by which heat dissipation rates are computed have previously been defined. Yet considerable engineering judgement must be applied in pond design to develop maximum cooling efficiency. Cooling pond design is, in its own right, an art since factors that are peculiar and variable to pond function must independently be analyzed in light of the saliant design aspects of cooling ponds. In addition to meteorological and heat transfer factors affecting pond design, other physical design parameters must be taken into account in determining the pond configuration, location and functional value.

a) Pond Depth: Acceptable depth of a cooling pond is dependent upon three factors (14):

1. Dry bulb temperature effects
2. Plant pumping rates
3. Retention time

As may be shown, the pond depth enters into our temperature decay equation in a subtle manner. If "V" is taken as pond volume, the average detention time in days would then be defined as:

$$t_d = V/F_p \tag{12}$$

Solving for "F_p" and letting "V/A" equal mean depth "d" the exponent "r" from Equation (11) becomes:

$$r = Kt_d/\rho d \tag{13}$$

Hence temperature drop increases as surface area increases. Generally, for a given pond volume, heat loading and meteorological conditions, a pond of greater surface area and less depth would dissipate more heat (7). As would be expected, for the same volume, evaporation rates for shallow ponds vary over a much wider range during the diurnal cycle than do those of deeper ponds, with the shallow ponds showing a higher maximum and lower minimum value (6). The slightly greater evaporation from shallow ponds is due to a greater inflow of heat from the overlying air.

One factor closely associated with depth is flow stratification. Water is a poor heat conductor so higher temperatures are found nearer the surface. This is aided by the lower density of warmer water. Posey and DeWitt (15) have stated that thermal stratification occurs because the detention time required for water to flow through the impoundment is not compatible with the rate of heat exchange between the surface and atmosphere. To avoid this, depth should be premised on the anticipated thermal budget and prevailing atmospheric conditions. If properly accounted for, it seems more reasonable to assume that the stirring caused by an inflowing stream combined with wind effects would produce a more nearly uniform temperature gradiant, and drastic unbeneficial changes as occur between epilimion and thermocline of a shallow pond could be avoided.

b) Separation of Intake and Discharge Points: No precise distance can be established for separation of inflow and discharge points. The distance is a function of the quantity of heat rejected, wind direction, pond depth and geographical configuration (14). One of the basic theories of cooling pond function is that warm water, upon entering a pond, will rise to the surface and spread out in a thin layer. Theoretical convective currents established by thermal gradients would distribute this warm water over the pond. Thus the temperature of the surface layer would be in direct proportion to the distance from the inflow. Test data (14), however, have shown that when warm water has an option of two paths it will follow the path of shortest distance to the discharge with no particular distribution, thereby demonstrating induced flow. Thorne states (16) that above ambient temperatures quickly dissipate after heated effluent enters the pond. Consequently, why should intake and discharge physical location be of importance? To evaluate this, attention should be directed to the previous section where time affects the exponential function of temperature loss as well as the logarithmic decay factors and the graphic representation of Figure II-2 showing area relationship to temperature loss.

c) Longitudinal Mixing and Diffusion: For specific meteorological conditions experiments have shown that the performance of a cooling pond in yielding low temperature at outfall locations is largely determined by the degree of longitudinal mixing and uniformity of flow between inflow and outflow locations (4). Both longitudinal mixing and flow short-circuiting tend to convey warmer water from inflow area to discharge point, thereby lowering the efficiency of the cooling pond. The control of both longitudinal mixing and short-circuiting between inflow and discharge are important to cooling pond performance, and can be effected through installation of transverse baffles to divert longitudinal flow and skimmers to take advantage of any vertical density stratification.

Diffusion represents one other factor closely related to longitudinal mixing. Eddy diffusion is a completely random function of turbulence and may be occurring in numerous ways in a shallow pond subject to constant flow. The phenomenon is directly related to velocity distribution (17) and occurs in an inline flow direction more readily than in a crossflow pattern because of the downpond flow rate. Diffusion has a tendency to increase the convective rate of heat transfer across boundaries in a system. Like longitudinal mixing, diffusion's full benefit can be realized by proper installation of flow control structures such as retention or flow routing devices.

CHAPTER III

EXPERIMENTAL INVESTIGATION

GENERAL

In this study only laboratory experimentation was performed. A model was constructed to represent a cooling pond. Inflow and outflow canals were provided and portable levees constructed to the same scale as the model. Wind and solar effects were not considered in operation of the model or adjusted for in results obtained.

Within the confines of the pond system, various levee arrangements were studied to define their effect on flow, residence time and velocity. Dye studies were utilized in order to measure these effects. Temperature studies were performed and utilized in correlation of various levee arrangement with temperature change and flow characteristics. Air temperature and humidity of the laboratory space were recorded in each run by standard meteorogical methods and temperature changes measured are tabulated with these conditions.

MODEL DESIGN AND LAYOUT

a) Design Parameters: An arbitrary prototype of a cooling pond consisting of 500 acres was modeled. The model was designed considering principles along general guidelines of Froude Number since, in low velocity flow of large bodies of water, gravity and inertial forces very often are of much greater importance than friction, consequently, design by Reynolds Number would be inappropriate since friction terms were considered insignificant in the component parts of the model involving the warm water flow. Table I of Appendix B presents the general relationships modeled and the defining equations used. Computations defining prototype, model and the experimental system are outlined in Appendix B.

Availability of research area defined the limiting parameters of the model system and dictated that a distorted model be used. A geometric scale of 1 in 800 horizontal and 1 in 10 vertical with resulting distortion ration of 1/80 were investigated. This ratio was chosen as satisfactory inasmuch as the Froude and not the Reynolds criterion was predominate. Furthermore, model behavior would not be seriously hampered by types of available construction materials and steps to incorporate artificial roughness into the model would not be necessary in view of both this distortion ration and the requirement that the model not be premised on friction values. Additionally, this factor justified using straight walls for simulated baffle levees, hereafter referred to as deflection levees or levees, rather than having them formed to a typical prototype side slope.

Generally, parameters and existing rules of thumb were researched and used in defining the basic prototype modeled. These rules related to flow rate and pond area utilized in the operation of a steam electric power generating facility. Estimated area of the prototype pond was approximated using the relationship of one acre per plant megawatt capacity for facilities employing recirculation of cooling water. This figure would be conservative in the case of a flow through pond. The cooling water flow may be estimated as one cubic foot per second per megawatt of plant capacity based on a 20°F condenser temperature rise. Flows for other temperature rises may be proportionately increased; the lower the incremental temperature over the condensers the greater the flow rate. The model flow and pond area were based on a hypothetical plant capacity of 500 megawatts with a condenser temperature rise of 17°F. Prototype velocities were assumed to be one foot per second in the inflow and discharge canals of the in-line cooling pond.

Based on the known flows in the model, the size tank and pump to maintain the required flow mechanics of the system was computed. Heat requirements were also computed based on the differential heat necessary to maintain reservoir water hotter than that discharged from the model.

b) Model Layout: The model was constructed of one-half inch exterior grade plywood to plan dimension shown in Appendix C. Sides were braced with metal strips and the floor of the model was supported on 2 in. x 4 in. beams. All splices and junctions in the wood were sealed using successive layers of caulking compound, quarter round wood filler and brush coats of fiber glass resin. Canal configurations were formed into two sides of the model, using openings that could be easily plugged to facilitate relocation of canal sections. To assist in flow measurement and depth regulation, wier sections of appropriate height were installed in each outflow canal. Holes were drilled in the enclosed end of the outfall canal to permit discharge from the pond to an outflow reservoir which consisted of a large shallow pan. One 55 gallon drum was fitted with a 3/4 in. adjustable valve and functioned as an inflow reservoir. One adjustable capacity pump was arranged to provide constant head for this reservoir by returning effluent from the models outfall reservoir. Temperature differentials over pond water were maintained in the returned effluent using three submersible strip heaters suspended in the inflow reservoir. A grid system set-up on the model dimension basis of one foot intervals was utilized to facilitate measurement locations and data correlation. Clamps and stands to support thermometers and burettes for dye injection were positioned at the inflow and outflow sides of the model. Figures III-1 and III-2 respectively, show the reservoir with submersible strip heater and pond with typical canal and deflection levee arrangement. With the basic pond model, two inflow and outfall canal locations were investigated and with each of these arrangements, four configurations for levee placement and orientation were investigated. Plan views of the

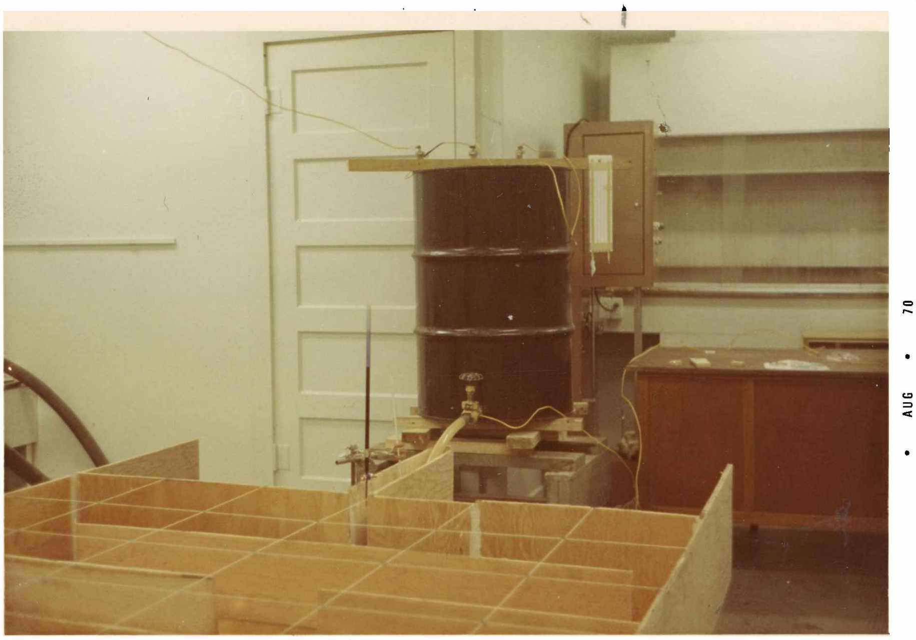


FIGURE III-1

INFLOW RESERVOIR, HEATER STRIP

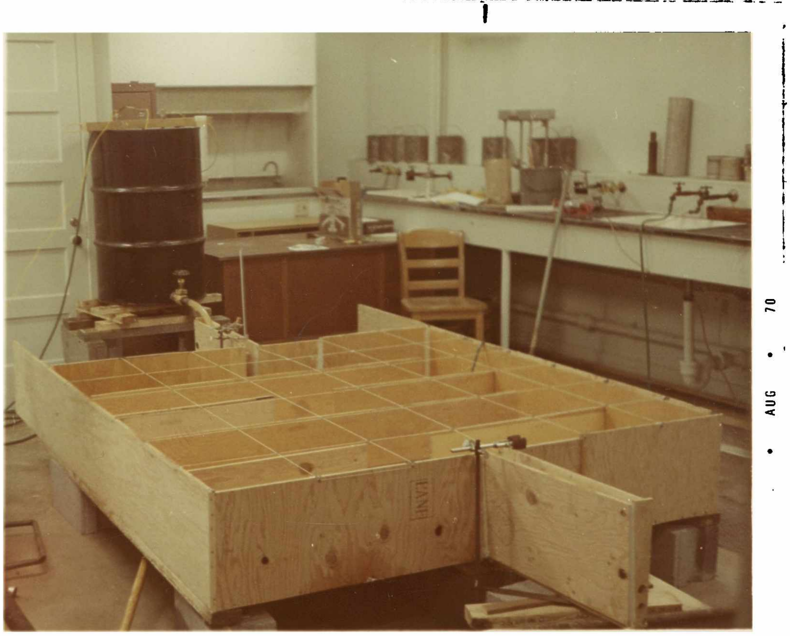


FIGURE III-2

OVERALL MODEL SYSTEM

configurations tested are outlined in Appendix C, Figures C-1 through C-8. Effects of length and width variation of basic pond model were not investigated.

EXPERIMENTAL PROCEDURE

Water depth was marked in the pond model and supporting reservoirs. Each of these were filled with water hotter than the research area yet regulated within safe working ranges of 95°F to 110°F. Room temperature and wet bulb temperature were recorded prior to each run. Accurate sensitive thermometers were installed at inlet and outlet canal positions. These thermometers were standarized by the United States Bureau of Standards and were graduated to 0.2°F with no correction required. The measured lower range response rate of these thermometers was established as 3.9°F per second. Thermometers of such high quality were judged more desirable in this study since the standard "yellow-back" which was tested did not accurately reflect the temperature change within the system.

At the start of each run, corks in the enclosed end of the outlet canal were pulled and the inlet valve on the supply reservoir was opened to begin flow. After the strip heaters of the inflow reservoir and the return supply pump had been plugged in, the flow rate regulation of the pump was rechecked. When flow regime had been stabilized, tests to determine surface velocities were conducted. This was accomplished by noting the time lapse required for a surface float to travel between coordinates. Flow patterns were also extrapolated by considering extended surface velocity studies. Velocity tests were conducted at intermediate points along the pond, depending upon the levee arrangement, and not necessarily centered at the inflow/outflow streamlines. Surface velocities were not measured when the levee system consisted of inverted wiers.

Subsurface velocities were determined in approximately the same areas as surface velocities. Fluorescein dye was used and injected at water mid-depth using a burette. Normally 3 to 5 ml of dye was used in each injection. The time lapse required for the downstream edge of the dye to flow between coordinates was noted and, subsurface velocity flow patterns were established. These velocity tests were conducted on all of the various levee arrangements investigated. Figures III-3 and III-4 represent a typical subsurface velocity test. The combination of the surface and subsurface velocity tests performed were quite useful in establishing "dead areas" of pond contribution to the overall thermal picture as discussed later.

After velocity tests had been performed, the flow was recirculated through the system to allow further dilution of the fluorescein dye. Temperature studies were then performed. The temperature reading of the

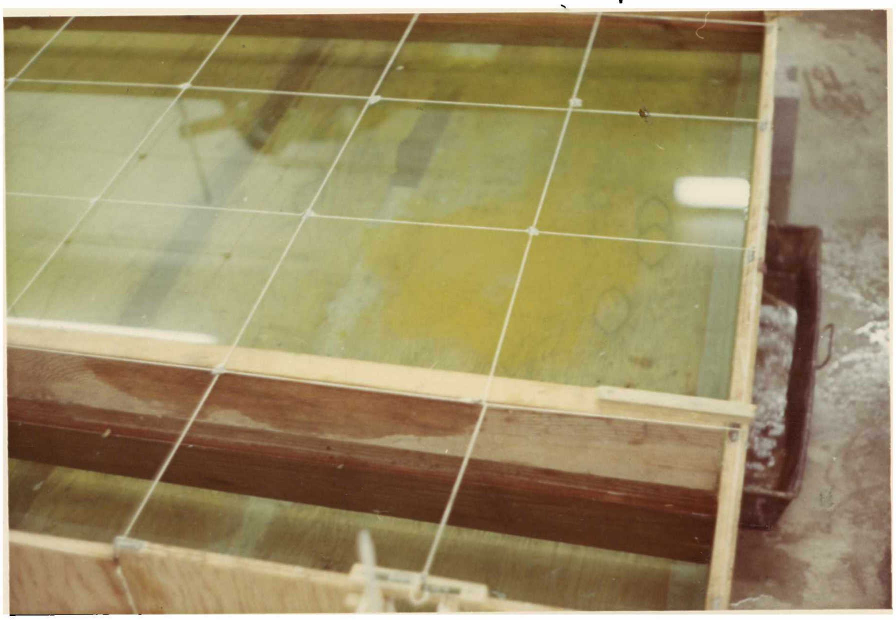


FIGURE III-3

SUBSURFACE VELOCITY TEST

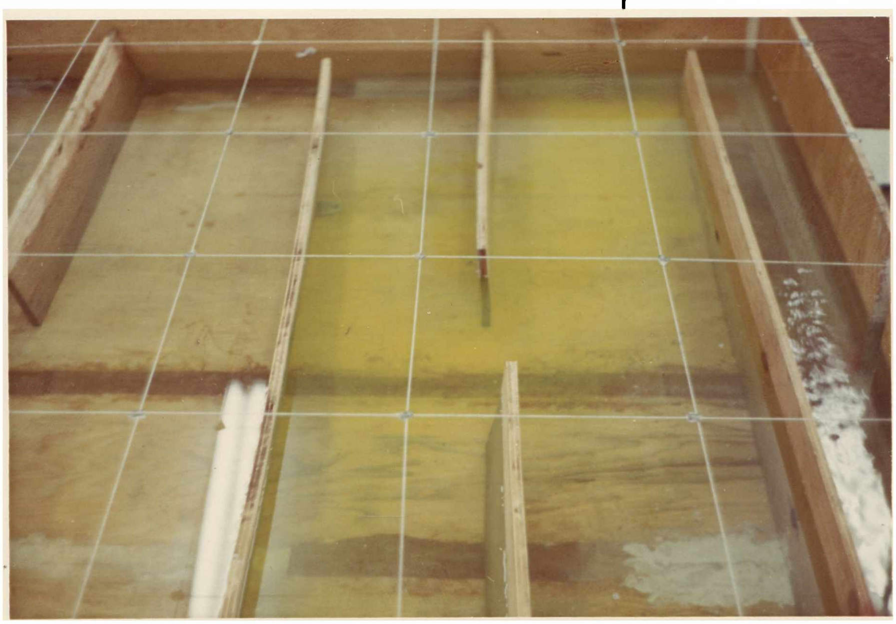


FIGURE III-4

SUBSURFACE VELOCITY TEST

incoming stream was noted from the control thermometer placed in the inlet. Between 15 and 17 ml. of dimethylene blue dye was injected into the flow at this point using a burette. Injection of dye was concurrent with temperature reading. Dimethylene blue dye was used in this phase of the experiment in an attempt to override any lingering traces of the flourescein dye used in the velocity tests. The time required for the dye to reach the effluent channel was noted and defined as model residence time. The temperature of the effluent was also recorded and defined as discharge temperature. When a particular test of anticipated long residence time was conducted, intermediate temperatures were read at specific coordinates. The downstream fringe area of the blue dye was used to define these coordinates and the point of temperature reading. It should be noted at this point that no particular steps were taken to insure that the model temperature matched the temperature of the prototype. This can be explained in two ways. The model was not designed from a planned or existing prototype; and, in the special case of zero wind velocity, the thermal exchange coefficient would, by necessity, be of comparable magnitude in both model and prototype if the water and equilibrium temperatures of each are equal. Since this is an impossible condition, the hydrodynamic and thermodynamic modeling of the heated discharge cannot be done using identical temperatures in both model and prototype.

CHAPTER IV

RESULTS AND DISCUSSION

GENERAL

This investigation included pilot plant studies on a model of a flow-through cooling pond. The tests were conducted in an attempt to define the efficiency of a fixed boundary pond as related to two positions of inflow and outflow canal location and various deflection levees located to form specific configurations within the fixed boundary. The channel and respective levee configurations for each test run are shown in Appendix C, Figures C-1 through C-8.

To assist in the tracing of flow patterns and measuring of velocities, dye tracing agents were used and injected into the water at various coordinates of the pond model. Although only one flow volume was investigated, several combinations of canal location and related levee arrangement were studied. Two tests for both velocity distribution and temperature gradient were conducted on the two canal configurations and each of their associated levee arrangements. Overall, a total of 16 experiments were performed on the fixed boundary cooling pond model. The detailed procedures followed in the experimentation were previously outlined in Chapter III. The results of the experiments are tabulated in Tables 1 through 16 in Appendix D and further discussed hereafter on an individual experiment basis. To supplement the tabulated data, graphic velocity distribution and flow vectors have been prepared and are included in this Chapter with the related experiment discussion. On an overall basis, the experimental data obtained appear consistant between runs and with the anticipated results.

ANALYSIS OF SPECIFIC RESULTS

Analysis of data gathered from Experiment I utilizing the pond configuration shown in Figure C-1 indicates that, without diversion systems and with in-line inflow and discharge canals, the warm water effluent followed the shortest distance to discharge. There is no apparent longitudinal dispersion of this water mass as it traverses the pond (Figure IV-1).

Review of combined velocity patterns (Figure IV-2) for each of the two runs indicates the centralized flow mass exerts a pulling or venturi effect on stagnant areas of the pond establishing some tendency for flow from these edges to the center, then to the discharge. The diffusion of convective currents with the warm water mass possibly accounts for some temperature loss in the model. It is felt that this loss would not be significant in a prototype should this flow pattern actually exist. The full area of the pond obviously has not been

FIGURE IV-1

EXPERIMENT 1

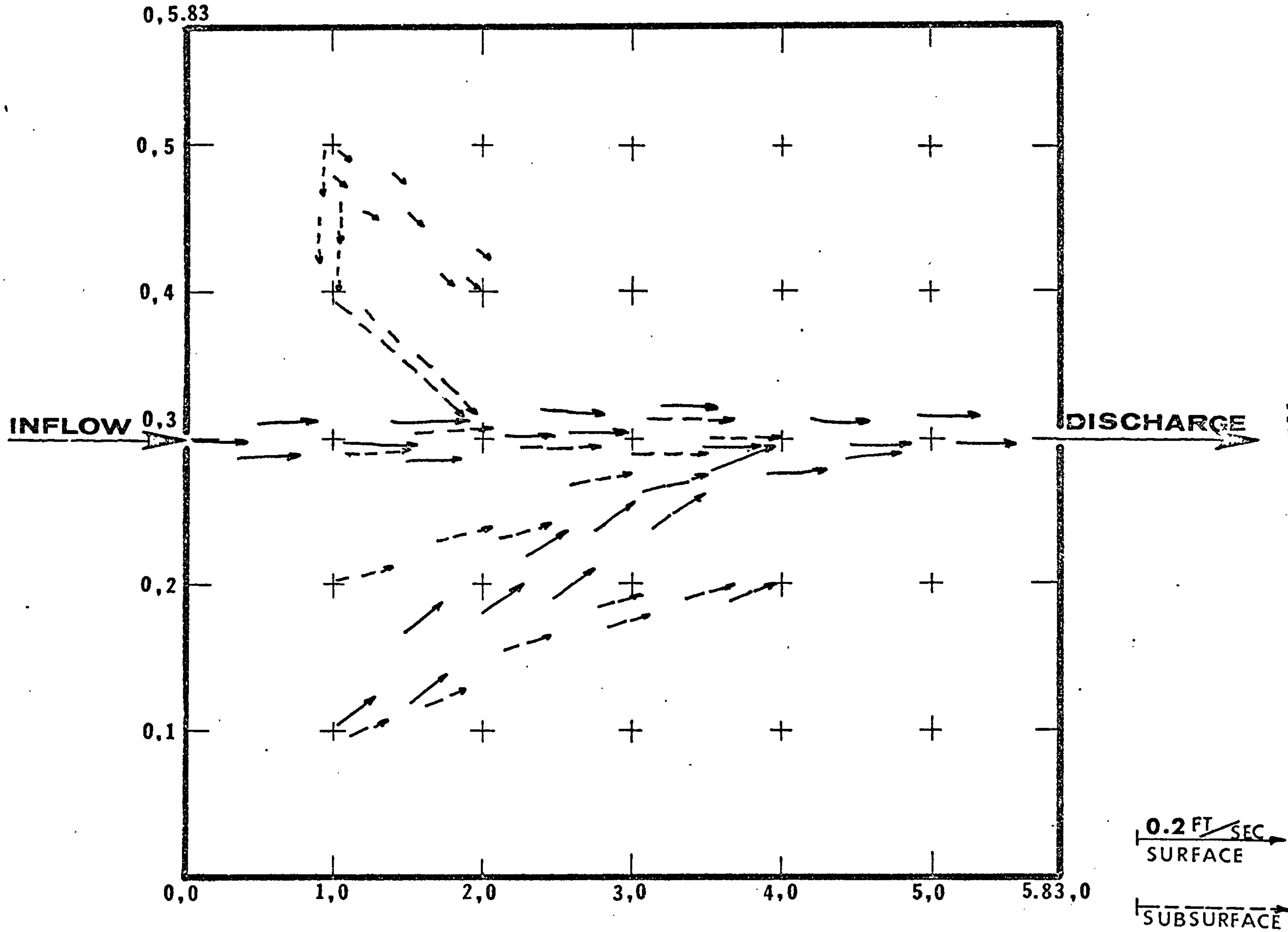


FIGURE IV-2
EXPERIMENT I

utilized and, by comparison, the apparent non-contributive portion is quite large. It is evident that the pond model has been short-circuited by the warm water flow.

Comparison of the data obtained from this experiment with that gathered from Experiment V using pond configuration as shown in Figure C-5 indicates similar behavior of the two systems. Although the velocity and flow patterns plotted (Figure IV-3) depict some tendency for the pond to be short-circuited by the flow, there is evidence of considerable more use of the pond area. This is accredited to the circulating pattern established by the eccentric inflow versus discharge locations. The presence of the dye visible in Figure IV-4 shows this circulating pattern. Analysis of flow regime during the experimental process verified that inflow equaled discharge and the dye dispersion is accredited to flow diffusion rather than test or model inadequacies.

An inverted wier retention system was investigated for each of the two channel configurations of the fixed boundary model (Figure C-2 and C-6). As may be witnessed from the graphic flow patterns plotted for each of these, (Figures IV-5 and IV-6) there is no drastic change in basic pattern between the inverted wier and the no deflection system previously discussed. There is, however, a considerable velocity change and subsequent increase in residence time. The area between the inflow and the first inverted wier takes on the appearance of a stablizing zone

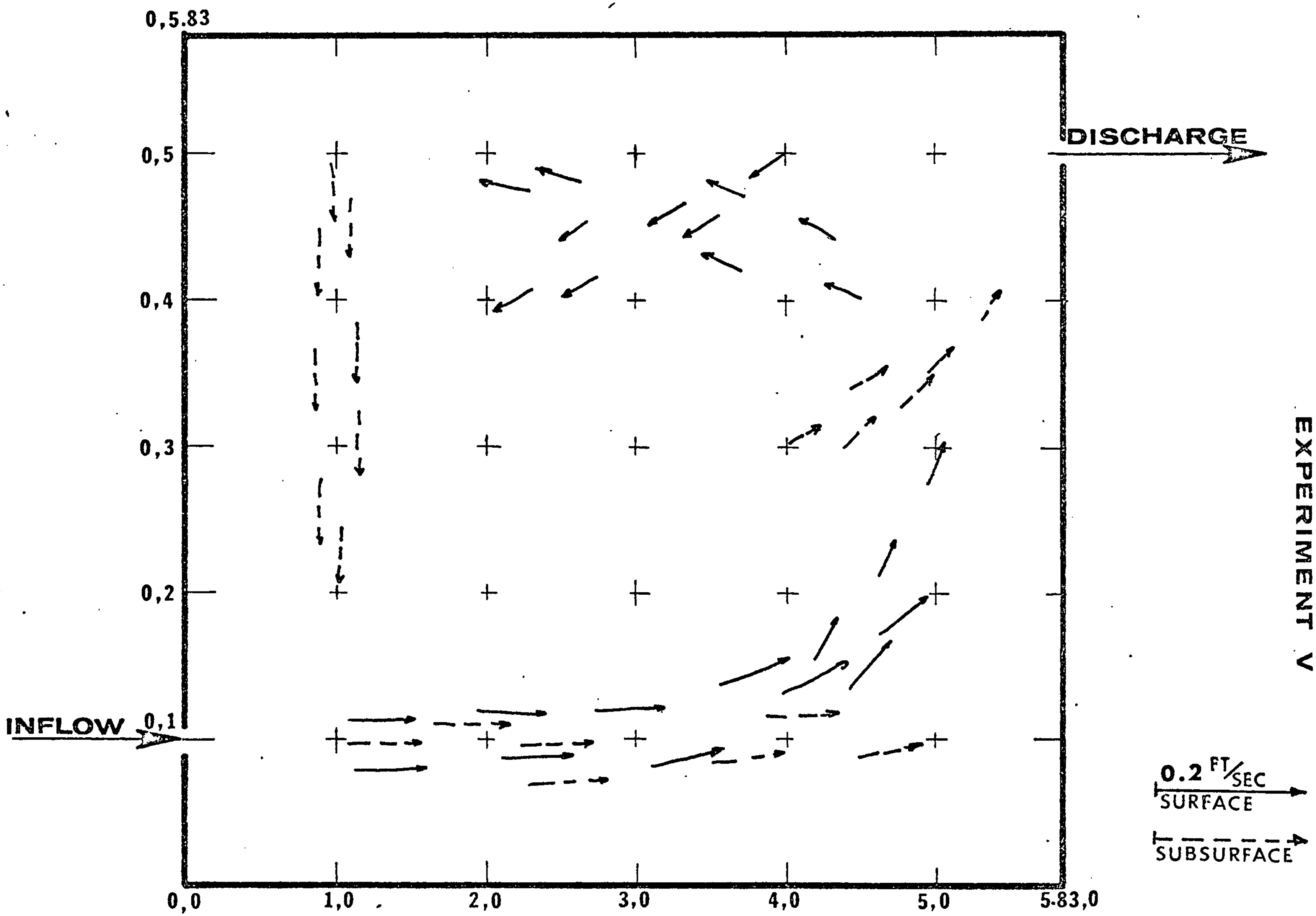


FIGURE IV-3
EXPERIMENT V

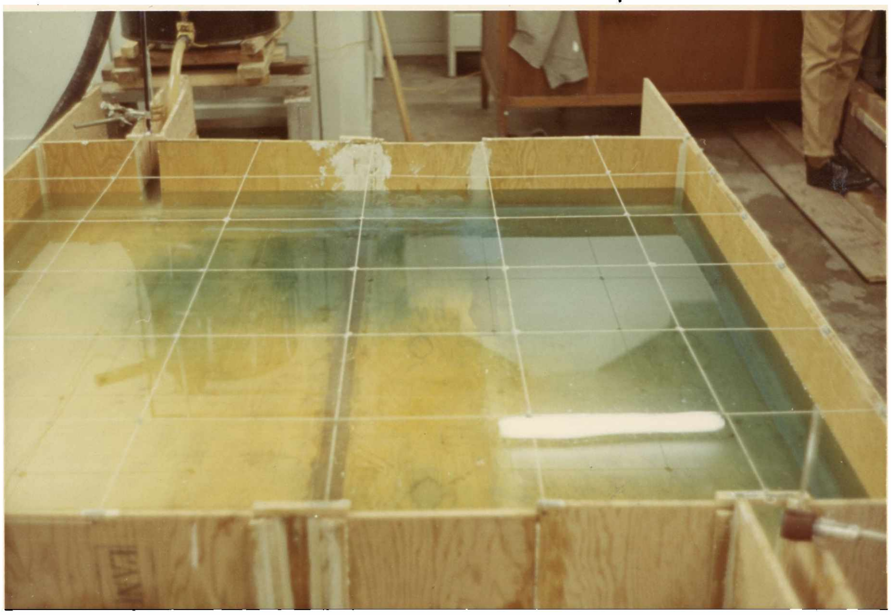


FIGURE IV-4

EXPERIMENT 5

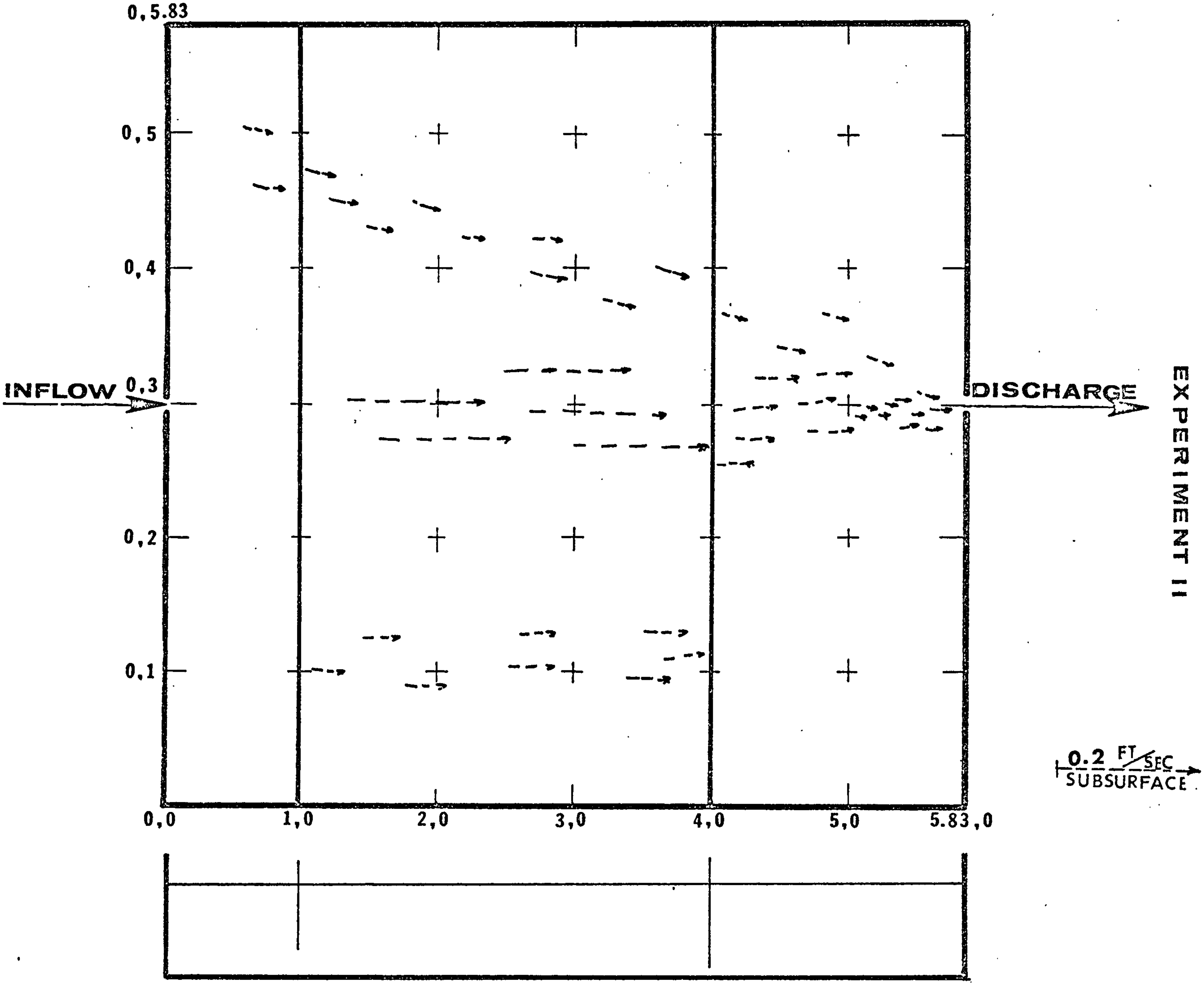


FIGURE IV-5
EXPERIMENT II

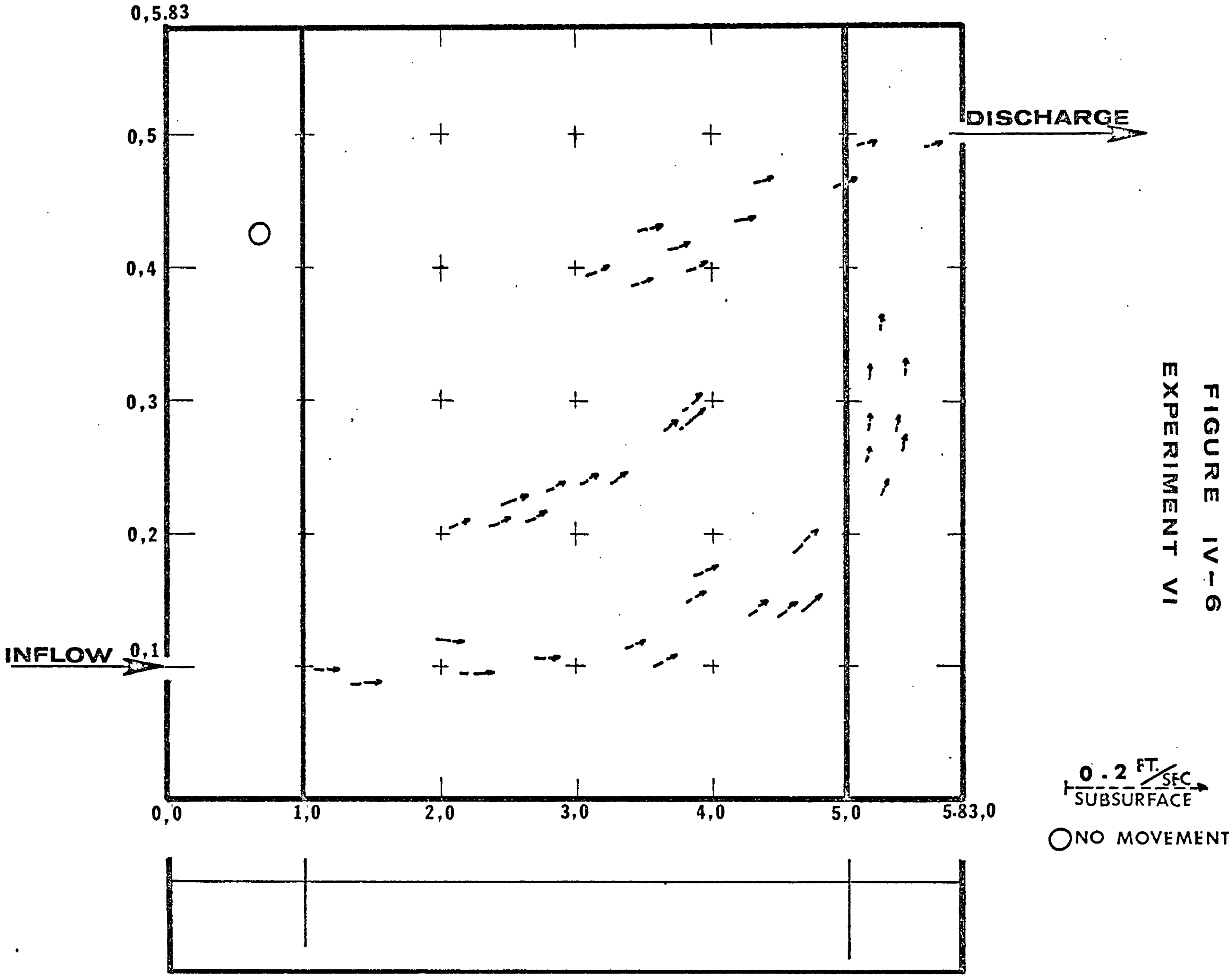


FIGURE IV-6
EXPERIMENT VI

where turbulence and momentum of inflow are reduced. A more uniform flow distribution is established past this wier (Figure IV-7 and Figure IV-8). From the data obtained in the previously discussed experiment using the configuration of Figure C-5, the greater temperature drop occurred in flow passing the second inverted wier.

Each of the inverted wiers in the configuration discussed above were placed at differing water depths. The first wier in each case was placed with the greatest depth of water below it, the second with the shallowest. As anticipated, the first wier acted as a flow stabilizer, absorbing most of the energy of the inflow, so its depth was not considered major provided the wier extended below half the water depth. The second wier was placed slightly deeper so as to act as a hot water deflector in the last phase of hot-water mixing and cooling. Its depth was premised on a maximum practical vertical travel distance for the surface heated effluent. Evidence of this vertical travel may be witnessed in the time lapse for injected dyes to appear on the downstream face of the wier.

A combination of deflection levees and inverted wier were investigated utilizing the pond configuration shown in Figure C-3. Analysis of the graphic flow and velocity patterns (Figure IV-9) associated with this arrangement indicates a rather large portion of the pond is stagnant. Figure IV-10 pictorally shows this by dye

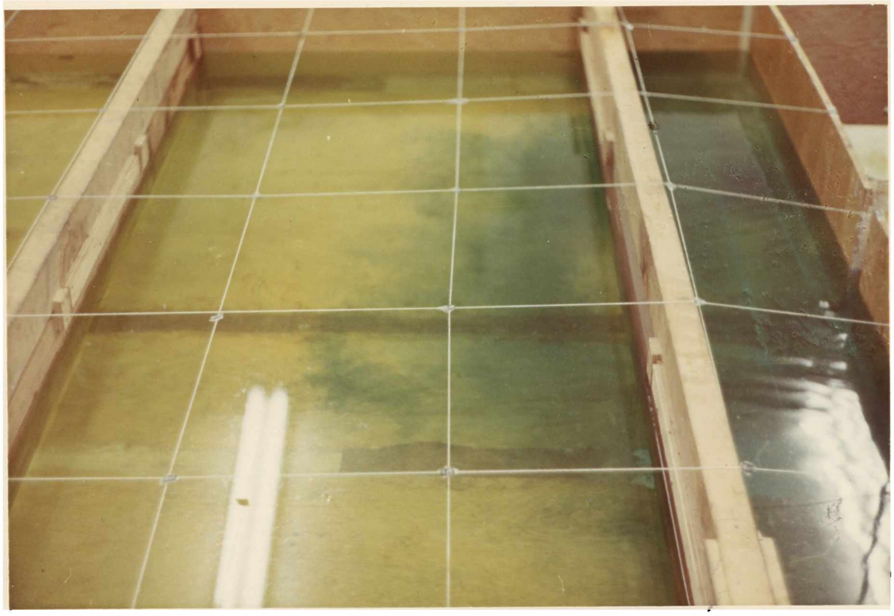


FIGURE IV-7

EXPERIMENT 2

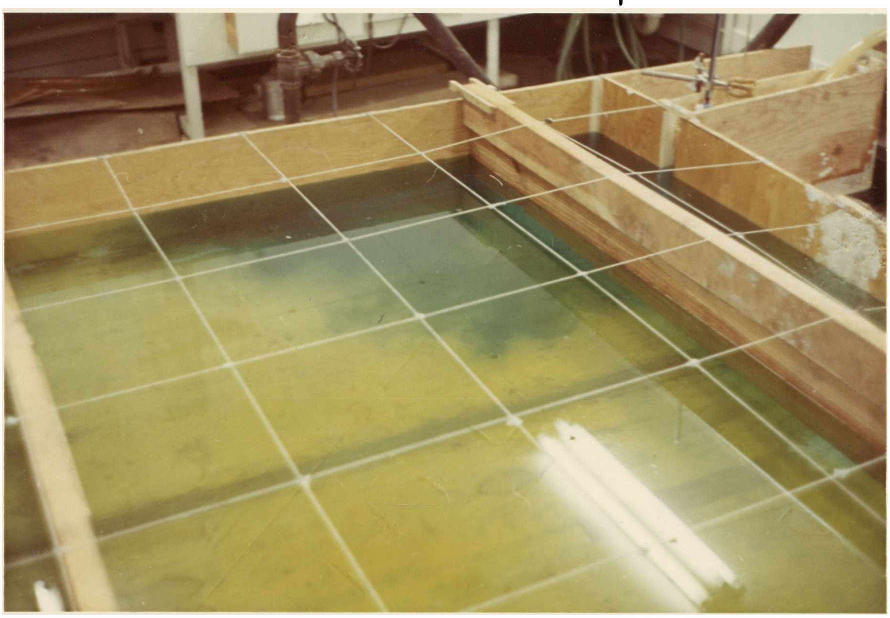


FIGURE IV-8

EXPERIMENT 6

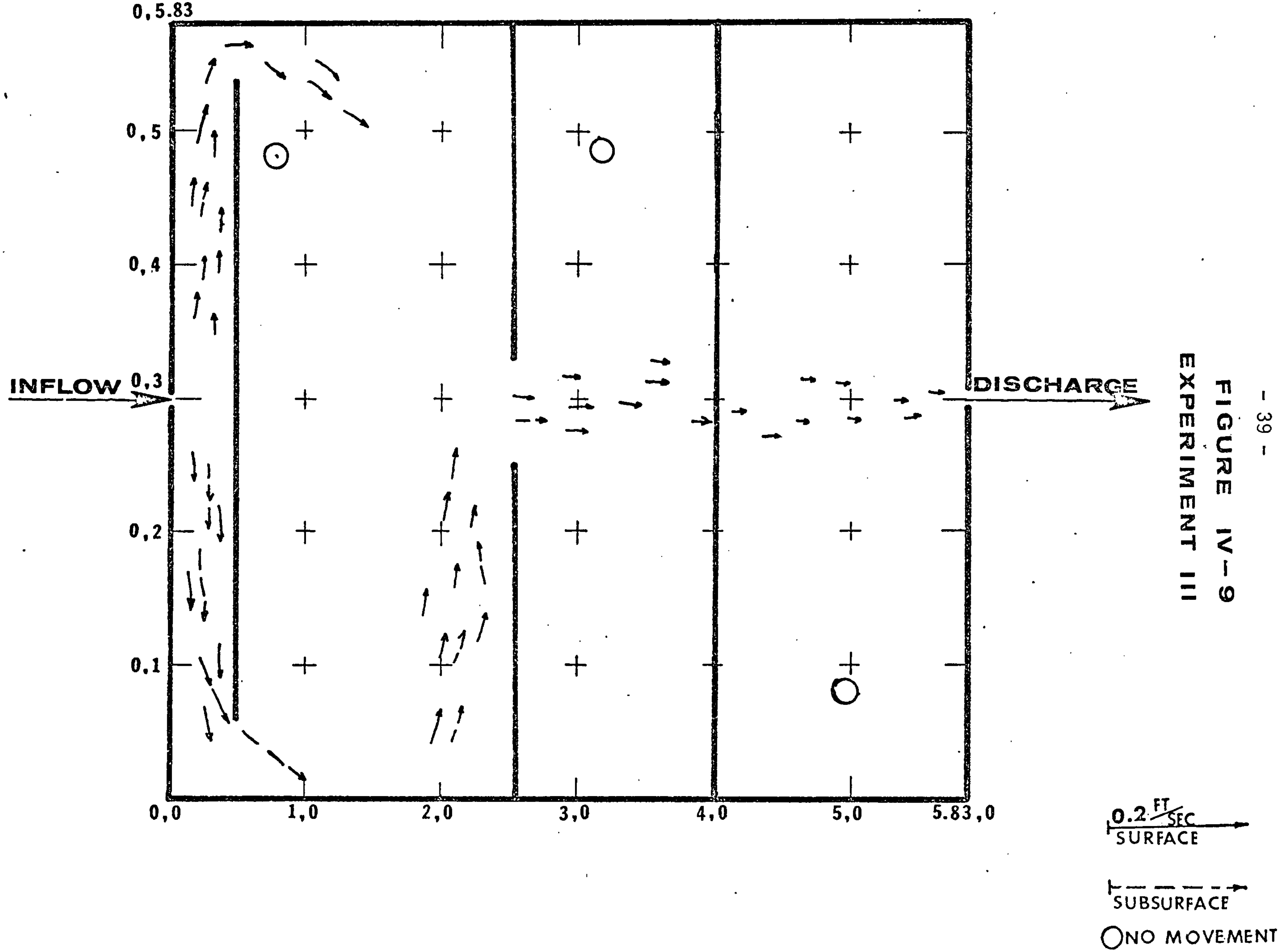


FIGURE IV-9
EXPERIMENT III

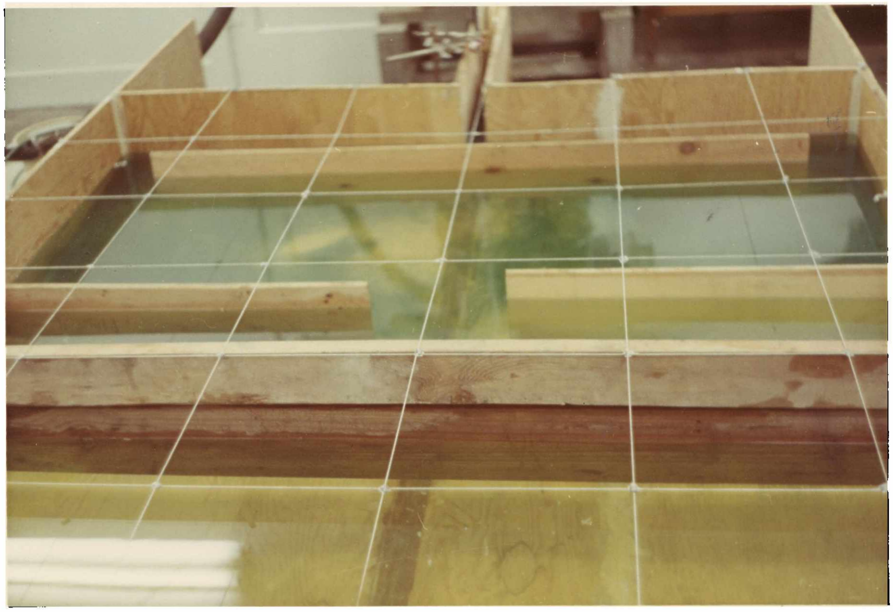


FIGURE IV-10

EXPERIMENT 3

dispersion along the fixed pond boundaries and adjacent to the shortened deflection levees with a major uncolored portion in the center of the picture and along the inflow deflection levee. The wier system used in this experiment was the same as the second wier of the previous two experiments.

It should be noted that, although the non-contributing portion of the overall pond was apparently a greater percentage in this experiment as compared to the last with the same canal configuration, the residence time was somewhat higher. This is attributed to the fact that velocity difference is not related to deflection levee arrangement. That is, a deflection system arrangement may increase the cooling contribution or area of a pond but they do not necessarily affect the velocities in the pond.

In an attempt to further verify the above statement, additional tests were performed utilizing the pond system and internal configuration as shown on Figure C-4. This configuration of deflection levees was believed to give the maximum utilization of the overall pond area for this particular canal configuration. This is supported by review of the dispersion pattern shown in Figure IV-11. Analysis of the data for subsurface velocities and of the flow pattern vector plot shown in Figure IV-12 verifies this. The velocity data obtained for both

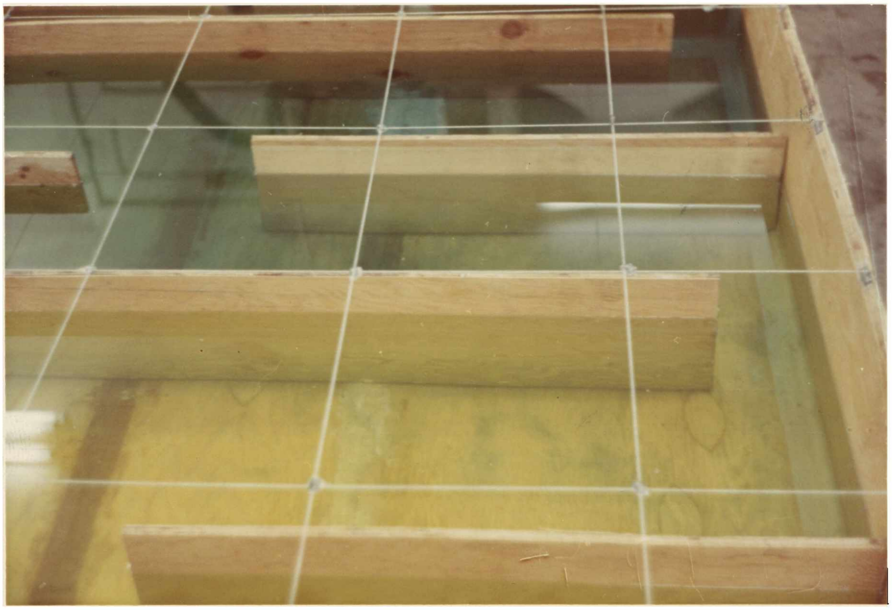


FIGURE IV-11

EXPERIMENT 4

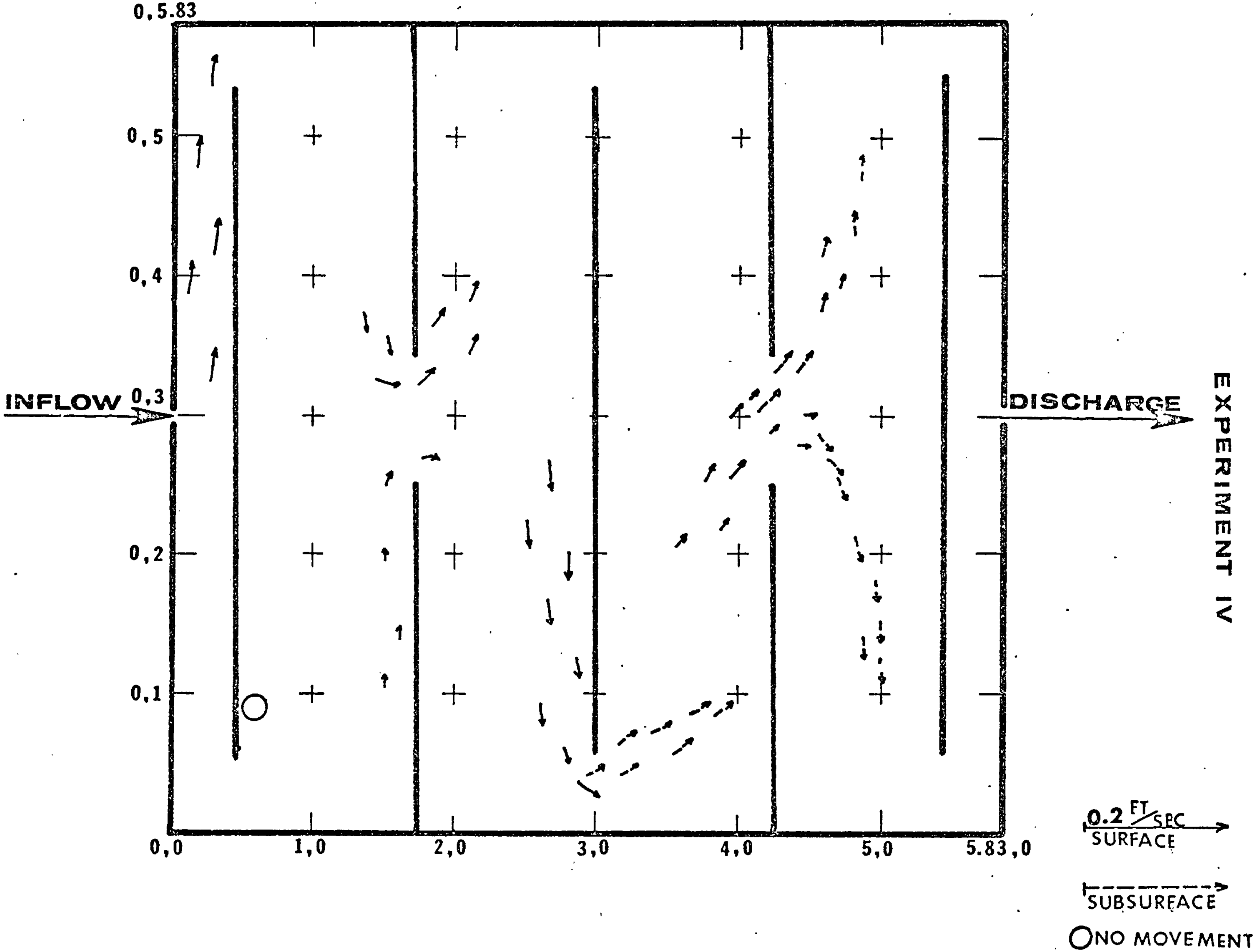


FIGURE IV-12
EXPERIMENT IV

experiments is somewhat low yet consistent, regardless of the coordinate location of velocity measurement.

The effect of channelized flow was investigated utilizing the more applicable offset channel arrangements shown in Figures C-7 and C-8. The pond was blocked off into a series of continuous channels aligned adjacent to each other yet possessing different hydraulic characteristics for each test. The wetted perimeter, water area and hydraulic radius is shown for one channel leg on the tabulated data sheet. Analysis of the flow patterns and velocity vectors for pond layout C-7 as shown in Figure IV-13 indicates a small segment of non-contributive area within the pond. This is substantiated by close analysis of the dye dispersion pattern shown on Figure IV-14 as the flow prepares to enter the adjacent channel. The same pattern is visible in the initial velocity vectors shown on Figure IV-15. As flow enters the second channel, a tendency exists to short-circuit the corners and border adjacent to the far side deflection levees. As may be witnessed from the data and comparison of Figure IV-14 with Figure IV-16 this tendency is reduced considerably in sequential channel stages placed closer together. It may be interesting to note that the least non-contributive areas and greatest residence time were encountered in the configuration possessing the least hydraulic parameters of area, wetted perimeter and hydraulic radius. This becomes obvious when reviewed in the light of Manning's

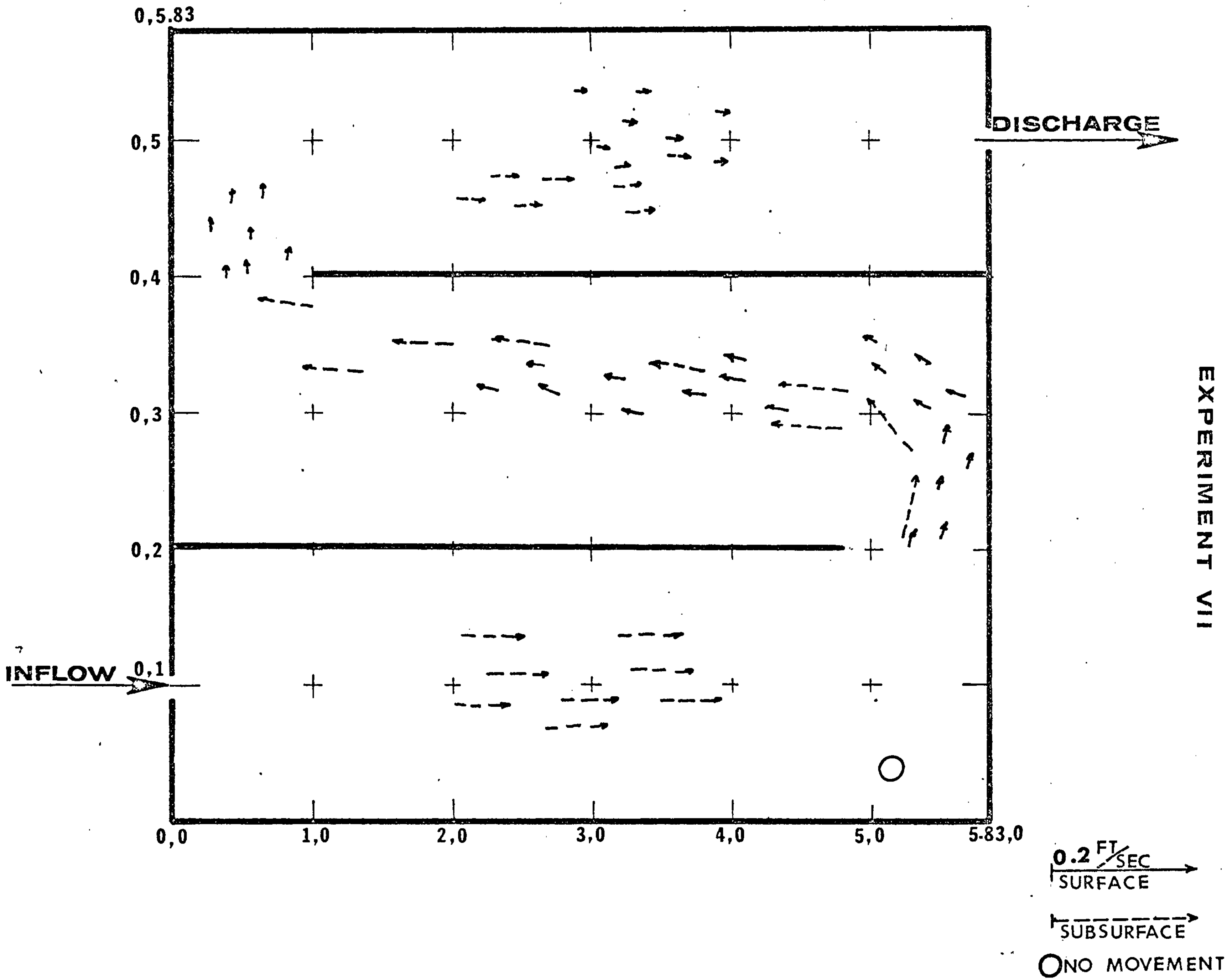


FIGURE IV-13
EXPERIMENT VII

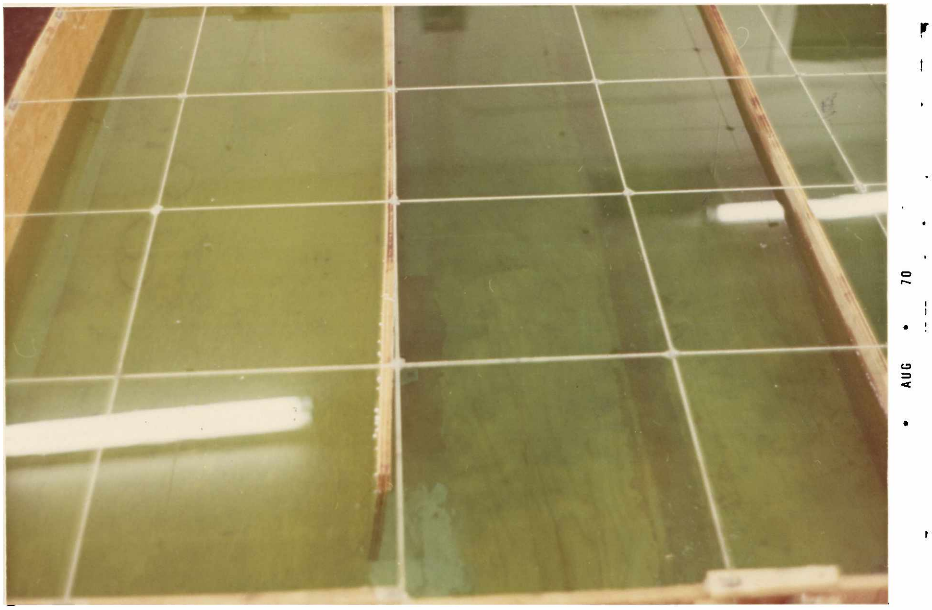
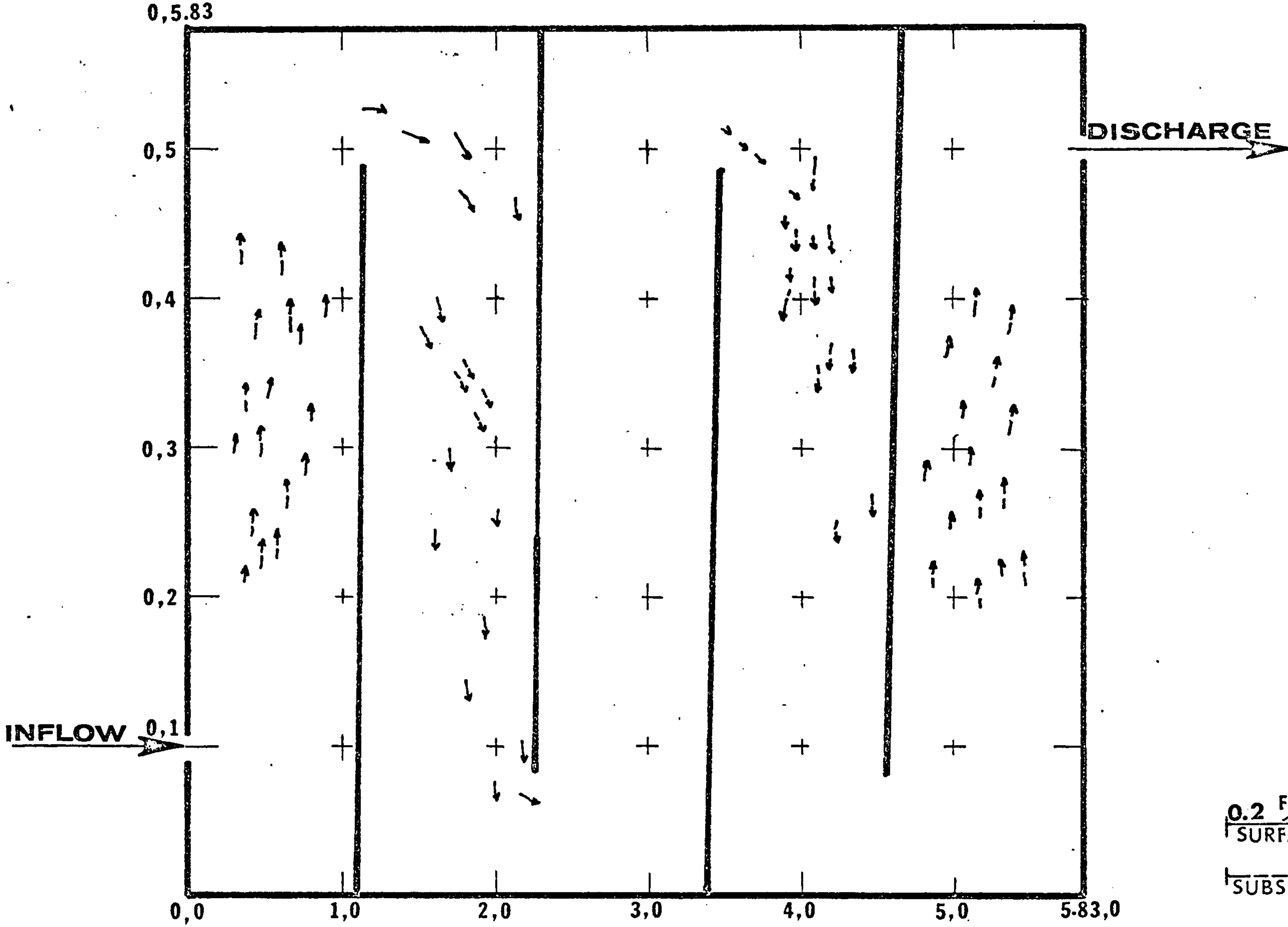


FIGURE IV-14

EXPERIMENT 7



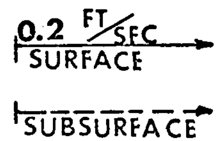


FIGURE IV-15
EXPERIMENT VII

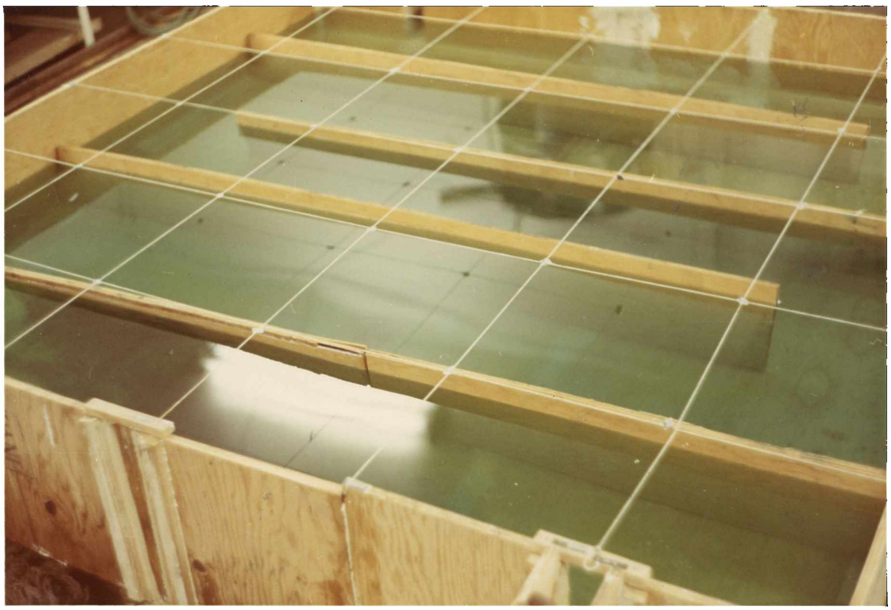


FIGURE IV-16

EXPERIMENT 8

flow equation for open channels.

COMPARABLE ANALYSES

In defining the efficiency of the pond system and its deflection configurations, the parameter of time rather than temperature change was chosen. This choice can be justified on the premise that temperature lost in the model was primarily from conduction while the same loss in a prototype would be accredited to evaporation, radiation and conduction. All three of these are related to time. Further support of this choice lies in the relationship that temperature loss is directly proportional to temperature difference. As mentioned earlier, model temperature could not equal prototype temperature; consequently, temperature loss would not be a representative efficiency parameter. Time is related in prototype and model by scale factors (Appendix B) and correlation presents no problems. The efficiency of the model system for this study is defined as:

$$\frac{\text{Actual Detention Time}}{\text{Maximum Available Detention Time}} \times 100\% \qquad (14)$$

The maximum detention time for the fixed boundary pond model may be defined by the relationship:

$$t_d = V_m F_m \qquad (15)$$

Using this as a guideline, the maximum detention time available for this model is 1255 seconds. The experimental data resulted in actual detention times extending from 27 seconds to 1103 seconds or efficiencies from 2.2% to 88.3%. In reviewing these efficiencies, it is possible to correlate them to some form of temperature change. This has been done in the graph of Figure IV-17. This curve is the transform of the least squares adjustment for the straight line equation shown in Figure IV-18 which represents a plot of the logarithmic values for the data obtained. The computer program used to obtain the equation defining this adjustment is given in Appendix F. Analysis of this curve indicates that it is, for practical purposes, the inverse of that plotted for the theoretical temperature loss versus area (Figure II-2) of a cooling pond, the only difference being that residence time has been substituted for area and temperature change inversely plotted. The composite meaning of these two figures is that full residence time must be developed in conjunction with available area if maximum cooling is to be accomplished within a pond area.

ANALYSIS OF EXPERIMENTAL ERROR SOURCES

In general, analysis of the data obtained from the experimental procedures would be of little value without some recognition of inherent sources of error in the data accumulation process.

a) Temperature Errors: As mentioned earlier, the mode of heat transfer predominant in this experiment was conduction. The heat loss to the system boundaries other than air has been neglected since the

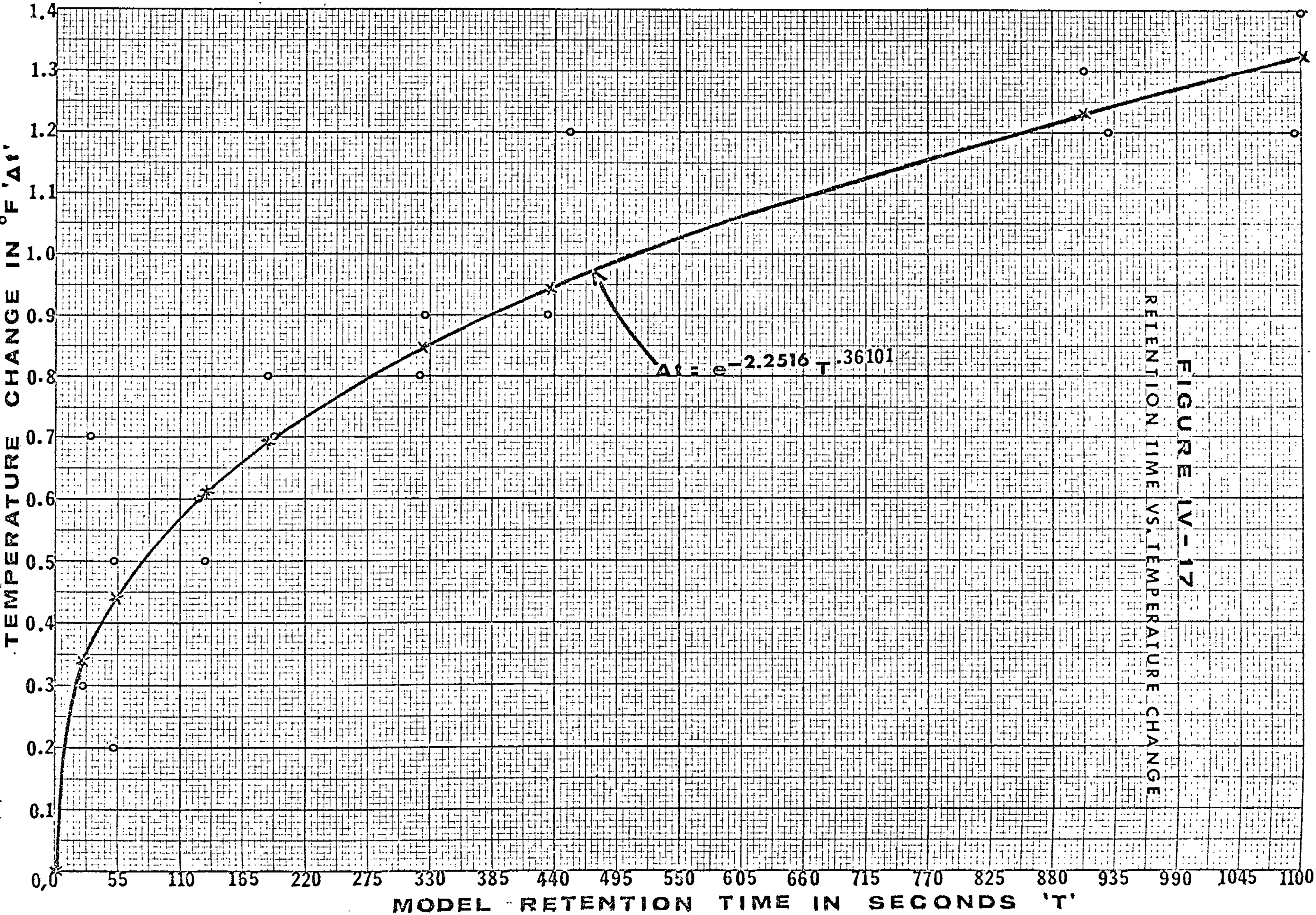


FIGURE IV-17
RETENTION TIME VS. TEMPERATURE CHANGE

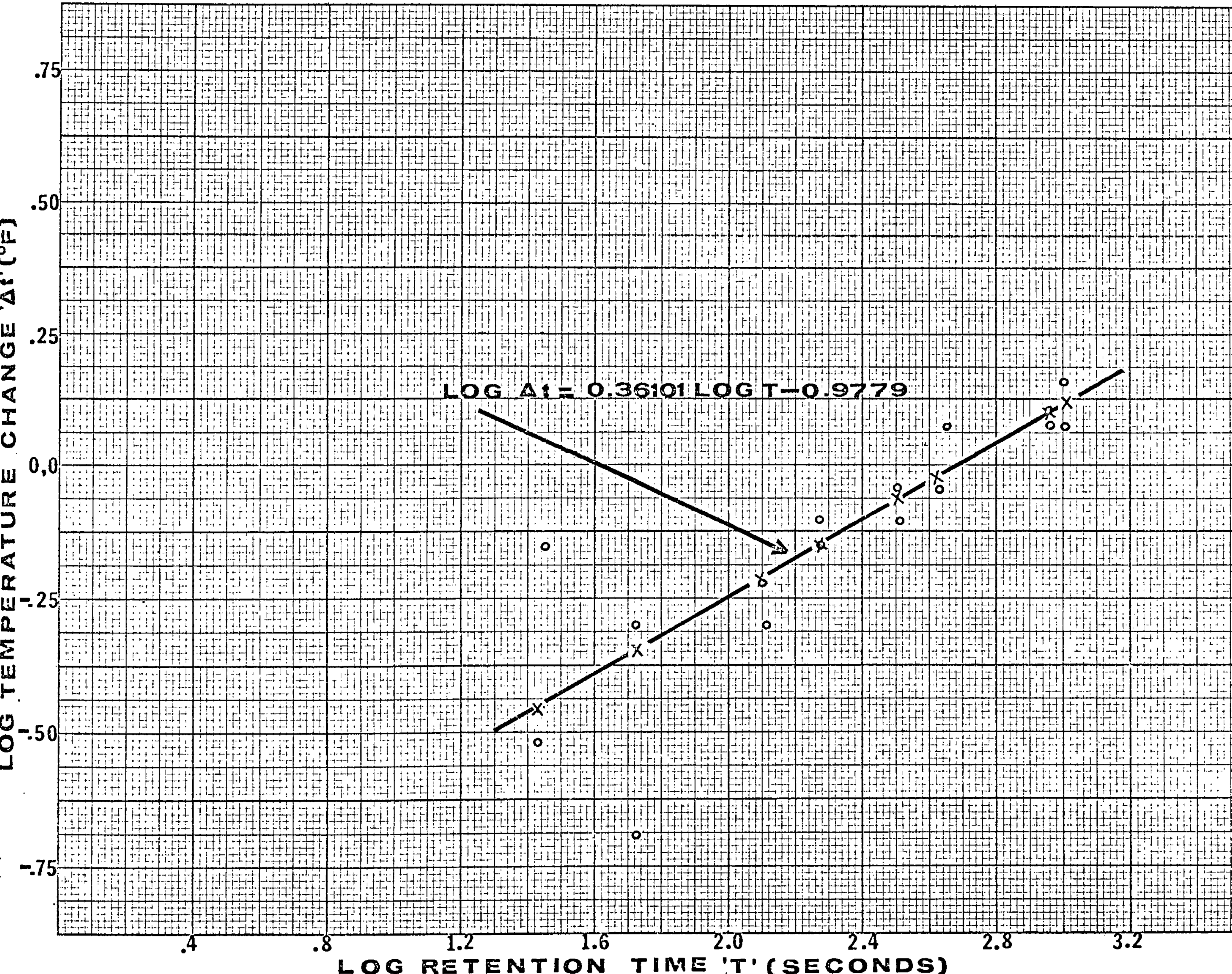


FIGURE IV-18

LOG RETENTION TIME VS. LOG TEMPERATURE CHANGE heat transfer coefficient of water to air is 0.373 and for water to wood it is 1/10 this or .037. This does not imply there is no temperature loss through the wooden restraint boundaries of the model; only that it has been ignored. Along the same lines, horizontal thermal eddy diffusivity and conductivity have been ignored because their contributions are held as insignificant when compared to horizontal two-dimensional convective transport. Attempts to compute the theoretical temperature of the model's effluent proved erratic and of little value.

b) Surface Velocity Errors: At low velocities of water flow, the main retarding effect between the water surface and atmosphere is shear. This force may well be sufficient enough to render erroneous values of surface float velocity. In the case where the water surface may be entrained and not affected by comparatively significant mass flow velocities, erroneous circulation patterns can also be established. For the purpose of this study, the differing eddy viscosities and related diffusivities that contribute to this shear force, are held as constant throughout the system boundaries.

c) Dye Dispersion Errors: From analysis of the data presented and experimental techniques utilized, considerable confidence has been placed on the use of dyes for describing the results. This method was considered acceptable since elaborate low velocity and flow measurement devices were not readily available. Generally speaking, dyes may be used to indicate the general pattern of subsurface currents by introducing them at the desired depth. The movement of the dye shows the direction of the currents; and the rate of dispersion is an index to the velocity. In this study a known amount of dye was injected to form a cloud and the uniaxial rate or downstream dispersion, based on coordinates and time, was recorded. This technique constituted subsurface velocity studies as well as heated water effluent flow patterns. By necessity, it assumes no vertical velocity stratification. Turbulent diffusion will transfer dye in the longitudinal direction and consequently the concentration of the dye may be decreased considerably at the points of measurement, yet the rate of horizontal transmission will not be affected.

Subsurface velocity measurements using flourescein dye releases were conducted prior to temperature measurements. The use of this dye was preferred because of its high decay rate and natural background blending levels, whereas the dimethylene blue dye, used to trace temperature patterns, is somewhat more permanent.

WASTE ASSIMILATION CHARACTERISTICS

Although no data were obtained that related directly to the waste assimilative characteristics of the model or its prototype, the data gathered can be utilized to formulate some comparison of a pond's capability in this area. Two phenomena were measured, recorded and checked relative to the pond's performance, temperature and residence time. Both of these are instrumental in certain processes of waste assimilation. Temperature plays a triple role by affecting the rate of pollutant oxidation, the dissolved oxygen capacity and the reaeration rate. Time, thus velocity, is related to the clarification and the sterilization by sunlight processes.

From the standpoint of environmental interest, cooling ponds can form desirable barriers to the transfer of pollutants across boundaries. As an example, consider some of the more pertinent factors listed:

a) Color: The bleaching action of sunlight on long exposure coupled with the coagulation and sedimentation processes are directly dependent upon residence time. These can all contribute to lower color concentrations of discharged waters.

b) Biochemical Oxygen Demand: The long term BOD of an elevated temperature inflow into a cooling pond can be significantly reduced through adequate residence time. The "smoothing out" of peak loads through dilution must also be considered. Depletion of dissolved oxygen by this process can occur, but sufficient supply may well be furnished by corss-boundary diffusion of new water inflow at stagnant areas of the pond, increased area of air/water interface and convective currents established by the cooling process.

c) Nitrification: The cooling pond acts as a retention basin for the conversion of certain strong pollutants, such as ammonia, to either nitrates or nitrites by allowing sufficient residence time for this to occur. As in the case of BOD, sufficient dissolved oxygen can be added by inflow, aeration and current turnover.

In cases where accidental gross contamination of the cooling water might occur, the pond serves as a retention basin where the contaminant can be detected and removed before discharge. If treatment is required, the concentrative effect of the pond may be advantageous because of a large reduction in quantity of water to be treated.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

The examination of literature on cooling pond performance and the experimental investigation conducted in this project were both instrumental in the formulation of conclusions that are both general and specific to the field of once through cooling pond design.

Cooling ponds are an acceptable and efficient device for the removal of heat from a thermal process industry's wastewater effluent. In their overall performance, many factors influence their rate of excess heat dissipation. Such factors include, but are not limited to, meteorological conditions, wind direction and speed, and difference between thermal loading and thermal equilibrium. Although atmospheric factors were not actively accounted for in this experimental study, they are considered a predominant factor in evaluating a cooling pond's performance as verified by the descriptive heat transfer equations formulated in the literature research.

Following is presented a list of conclusions that are based on this study:

1. The use of physical modeling to describe the cooling phenomena of ponds represents an impractical approach when viewed in perspective of the complete thermal isolation required to verify and balance the results obtained.

2. Deflection system arrangements may increase the cooling contribution or area of a pond but they do not affect the flow velocities within the pond system.

3. Installation of center-line off-set canals for a once-through cooling pond provides greater flexibility for utilization of the available water surface area. By comparison, an open pond system with off-set canals increased residence time by 50 percent of an inline canal open system.

4. Inverted wiers are an effective means of cooling heated discharges, particularly when velocity reduction barriers are provided. As established in this experiment inverted wiers alone decreased the average discharge temperature by 60 percent over an open system. When used in conjunction with barriers to reduce velocity, the decrease was 150 percent.

5. Deflection structures are integral to a once through cooling pond system in that they control longitudinal mixing, eliminate pond short-circuiting and insure maximum surface area dispersion of heated effluent.

6. Channeled flow consisting of minimized hydraulic conveyance parameters as compared to randum diversion of flow provides greater residence time within a cooling pond system. Data obtained in this experiment verified that channeled flow through minimized conveyance parameters increaded the pond's efficiency by 15 percent over random diversion.

The results of the studies performed in this experimental project suggest recommendations for more research in these areas:

1. The effect of width versus length and other geometric configurations should be evaluated to further define cooling pond efficiency.

2. The waste assimilative capacity of once through cooling ponds should be investigated.

3. Analyses on the effect of water depth to cooling pond performance should be conducted.

BIBLOGRAPHY

1. Brown, F. S., "Disposal of Heat From Power Generating Stations - Problems, Uses and Research," Society of Civil Engineers, Preprint, 1019, October 16, 1969.

2. Garay, P. N., "Design Considerations in Selecting Water Cooling Systems," Consulting Engineer, Volume 26, No. 1 page 92, January, 1966.

3. Braswell, R. W., "Cooling Pond Proves Cheaper," Electrical World, page 84, November 30, 1953.

4. Brady, D. K., Graves, W. L. and Geyer, J. C. "Surface Heat Exchange at Power Plant Cooling Lakes," Edison Electric Institute, EEI Publication No. 69-901, November, 1969.

5. Rapheal, J. M., "Prediction of Temperatures in Rivers and Reservoirs," Journal of the Power Division Society of Civil Engineers, No. 3200, PO-2 July, 1962.

6. Ferguson, J., "Rate of Natural Evaporation from Shallow Ponds," Australian Journal of Scientific Research, Volume 5, No. 2, page 315, June, 1952.

7. Edinger, J. E. and Geyer, J. C., "Heat Exchange in the Environment," Edison Electric Institute, EEI Publication No. 65-902, June, 1965.

8. Raphael, J. M., "Temperature Phenomena and Control in Reservoirs," U. S. Department of Health Education and Welfare, Water, Temperature, Influences, Effects, and Control. Proceedings of the 12th Pacific Northwest Symposium on Water Pollution Research, 1963.

9. Velz, C. J. and Gannon, J. J., "Forecasting Heat Loss in Ponds and Streams," Water Pollution Control Federation Journal, Volume 32, page 392, April, 1960.

10. Edinger, J. E. and Geyer, J. C., "Analyzing Steam Electric Power Plant Discharges," Journal of the Sanitary Division Society of Civil Engineers, No. 6064 SA-4 August, 1966.

11. Harbeck, G. E. Jr., "The Use of Reservoirs and Lakes for the Dissipation of Heat," Geological Survey Circular 282, U. S. Department of Interior, 1953.

12. Lima, P. O., "Pond Cooling By Surface Evaporation," Power, Volume 80, No. 3, page 142, 1936.

13. Langhaar, J. W., "Cooling Ponds May Answer Your Water Cooling Problem," Chemical Engineering, page 194, August, 1953.

14. Cotter, T. J. and Lotz, A. W., "Cooling Pond Design in the Southwest," Journal of the Power Division Society of Civil Engineers, No. 2861, PO 2, July, 1961.

15. Posey, F. H., and DeWitt, J. W., "Effects of Reservoir Impoundment on Water Quality," Journal of the Power Division Society of Civil Engineers, No. 7041, January, 1970.

16. Thorne, R. F., "How to Predict Lake Cooling Action," Power, Volume 95, page 86, September, 1951.

17. Parker, F. T., "Eddy Diffusion in Reservoirs and Pipelines," Journal of the Hydraulics Division Society of Civil Engineers, No. 2825, Volume 87, HY-3 May, 1961.

18. Krenkel, P. A., Thackston, E. L., and Parker, F. L., "Impoundment and Temperature Effect on Waste Assimulation," Journal of the Sanitary Division Society of Civil Engineers, No. 6406, SA 1, February, 1969.

19. Chruchill, M. A., "Effect of Storage Impoundments on Water Quality," Transaction American Society of Civil Engineers, Volume 123, page 419, 1958.

APPENDIX

APPENDIX A

NOTATION

APPENDIX A

NOTATION

B.O.D.	= Biochemical Oxygen Demand
B.T.U.	= British Thermal Units
$FT.^2$	= Square Feet
$FT.^3$	= Cubed Feet
^oF	= Degrees Fahrenheit
^oR	= Degrees Rankin
Q_a	= Rate of long wave atmospheric radiation in $BTU/FT^2/HR$.
Q_{br}	= Rate of back radiation in $BTU/FT^2/HR$.
Q_c	= Rate of heat conduction from water surface to air in $BTU/FT^2/HR$.
Q_e	= Rate of heat loss by evaporation in $BTU/FT^2/HR$.
Q_p	= Rate of gross heat input from artificial source in $BTU/FT^2/HR$.
Q_i	= Rate of net heat input from solar isolation $BTU/FT^2/HR$.
Q_s	= Rate of heat input from direct solar radiation in $BTU/FT^2/HR$.
Q_r	= Rate of reflected solar radiation $BTU/FT^2/HR$.
C	= Ratio of cloud cover to total sky are in tenths. A pure number.
C_w	= Specific heat of water, normally 1 $BTU/LB/^oF$.
K	= Heat exchange coefficient in $BTU/FT^2/HR/^oF$.
B	= Bowens ratio or proportionality constant.
A	= Lake area in FT^2.

V = Lake volume in FT^3.

F_p = Plant heated effluent discharge rate in FT^3/HR.

L = Average monthly station load in Kw.

P = Atmospheric pressure in inches of mercury.

R = Average monthly station net heat rate in BTU/Kwhr.

U = Wind velocity in knots.

T = Equilibrium temperature in ^oF.

T_a = Dry bulb air temperature in ^oF.

T_l = Lake temperature in ^oF.

T_p = Plant discharge loading temperature in ^oF.

T_w = Water surface temperature in ^oF.

T_6 = Air temperature at six feet above water level in ^oF.

k = Local measured heat transfer coefficient in BTU/FT^2/HR.

e = 2.7183

e_a = Vapor pressure of water in air in millimeters of mercury.

e_b = Average monthlystation boiler efficiency in %/100.

e_t = Average monthly station thermal efficiency in %/100.

e_w = Vapor pressure of water in saturated air at Tw in millimeters of mercury.

e_6 = Air vapor pressure measured six feet above water level in millimeters of mercury.

in. = Inches

ml. = Milliliters

% = Per cent

mm	= Millimeters
LBS	= Pounds
KW	= Kilowatts
HR	= Hours
α	= Average altitude of the sun in degrees.
ρ	= Density of water, 62.4 LBS/FT^3.
γ_w	= Emissivity of water, normally 0.97. A pure number.
σ	= Stephen - Boltzman constant, 1.714×10^{-7} $BTU/FT^2/HR/{}^\circ R^4$.
β	= Empirical constant defining the effects of vapor pressure and cloud cover on atmospheric radiation.

APPENDIX B

MODEL DESIGN PARAMETERS AND COMPUTATION

APPENDIX B

<u>Notation:</u>

λ = Models horizontal dimensional scale = 800

χ = Models vertical dimensional scale = 10

C_p = Flow velocity in prototype, feet per second

C_m = Flow velocity in prototype, feet per second

V_m = Volume of model in FT^3

F_p = Flow rate in prototype, same as plant effluent discharge rate

F_m = Flow rate in model, cubic feet per second

t_p = Time in prototype, seconds

t_m = Time in model, seconds

$\mathcal{F}_p$ = Froude Number in prototype

$\mathcal{F}_m$ = Froude Number in model

APPENDIX B

TABLE I

MODEL DESIGN PARAMETERS

Symbol Used	Parameter Defined	Prototype Value	Model/Prototype Definition	Model Value Empirical	Model Value Numerical
λ	Horizontal	1	λ	λ	800
χ	Vertical	1	χ	χ	10
C	Velocity	1	$\chi^{\frac{1}{2}}$	$C_p \chi^{-\frac{1}{2}}$	0132
F	Flow	610	$\lambda \chi^{3/2}$	$F_p / \lambda \chi^{3/2}$	.0241
t	Time	Computed	$\lambda \chi^{-1/2}$	$t_p / \lambda \chi^{-\frac{1}{2}}$	252.9 t_m
A	Area	2.178×10^7	λ^2	$A_p \lambda^{-1/2}$	33.99
L	Linear	4,667	$1/\lambda$	$1/\lambda$	5.83
D	Depth	6.5	$1/\chi$	$1/\chi$	0.538
$\mathcal{F}$	Froude Nº	.0018	$C/\sqrt{gD}$	$C/\sqrt{gD}$	.0018

Supplementary Computations

a) Head in Reservoir - 3/4 inch valve.

$$Fm = Ca\sqrt{2gh}$$

$$.0241 = .6204 \times .7854 \times .0625^2 \; 64.34 \times h$$

$$h = 2.5 \text{ ft.} = 30 \text{ inches}$$

b) Heat Requirements for T=2°F

$$Q = m\,(T_2 - T_1)$$

$$M = 11 \text{ gpm} \times 8.33 \text{ lb/g} \times 60 \text{ min/hr} = 5497.8 \text{ lb/hr}$$

$5498 \times 2^{o}F = 10,996$ BTU/hr

$10,996$ BTU/hr $\times .2931$ Watt $= 3223$

$Q = 3$ KW.

c) Constant Head Pump Size

$F_{pump} = (.0241\ ft^3/sec \times 60\ sec/min) \div 7.48\ ft^3/gal$

$F_{pump} = 10.8$ GPM.

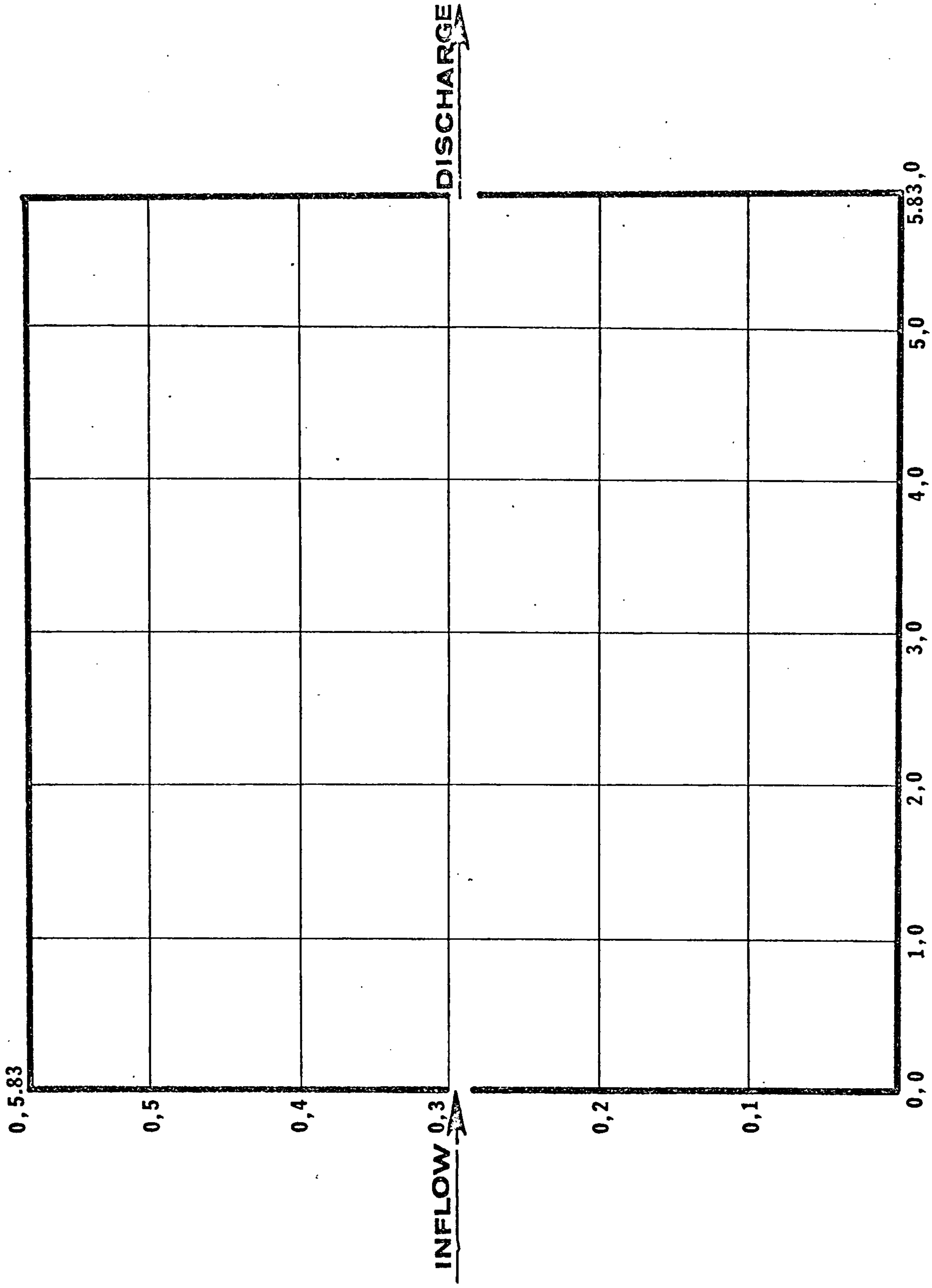
APPENDIX C

MODEL LAYOUT AND EXPERIMENTAL CONFIGURATIONS

APPENDIX C

FIGURE C-1

EXPERIMENT I



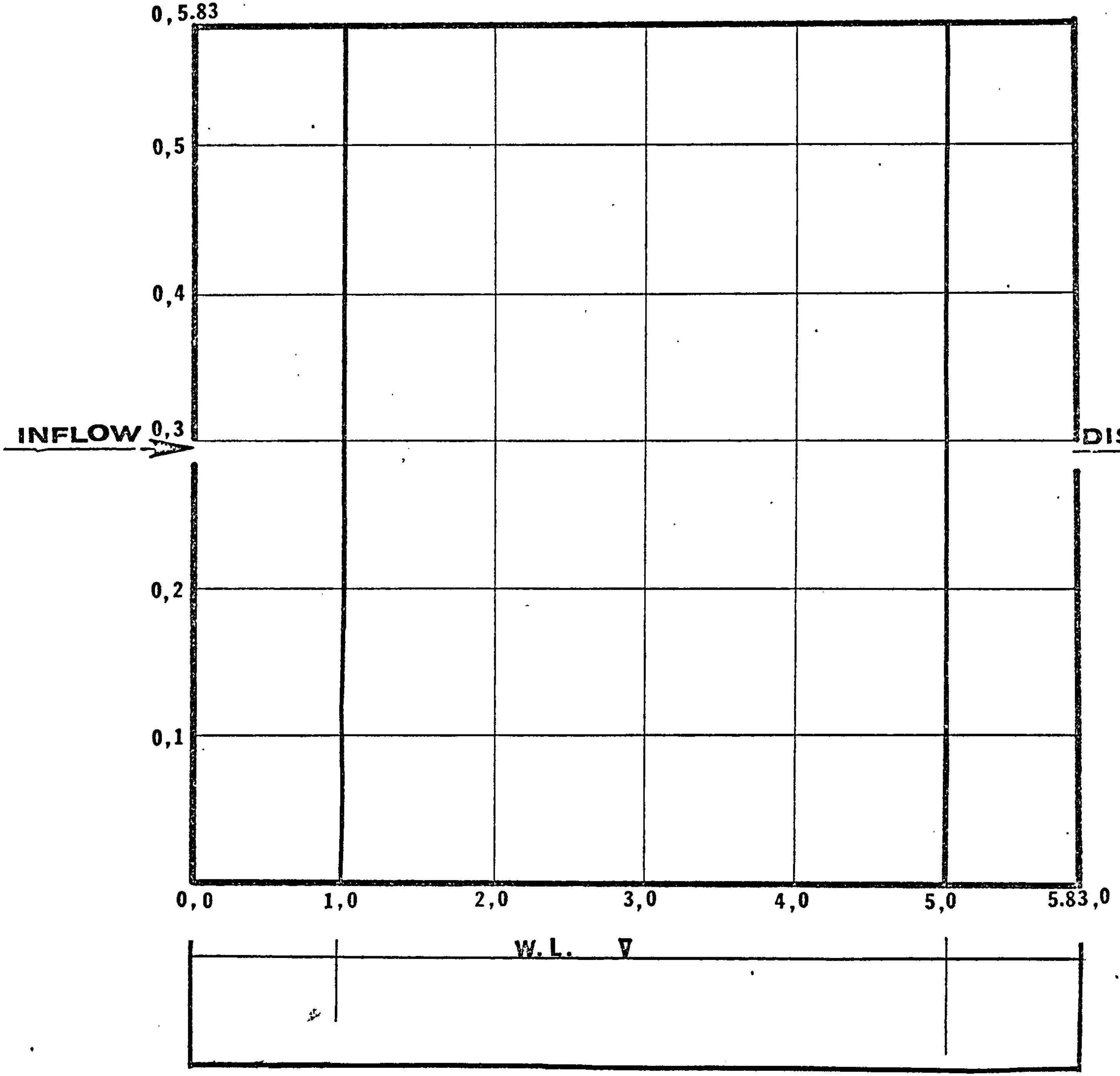
INLINE CANALS

NO DEFLECTION SYSTEM

APPENDIX C

FIGURE C-2

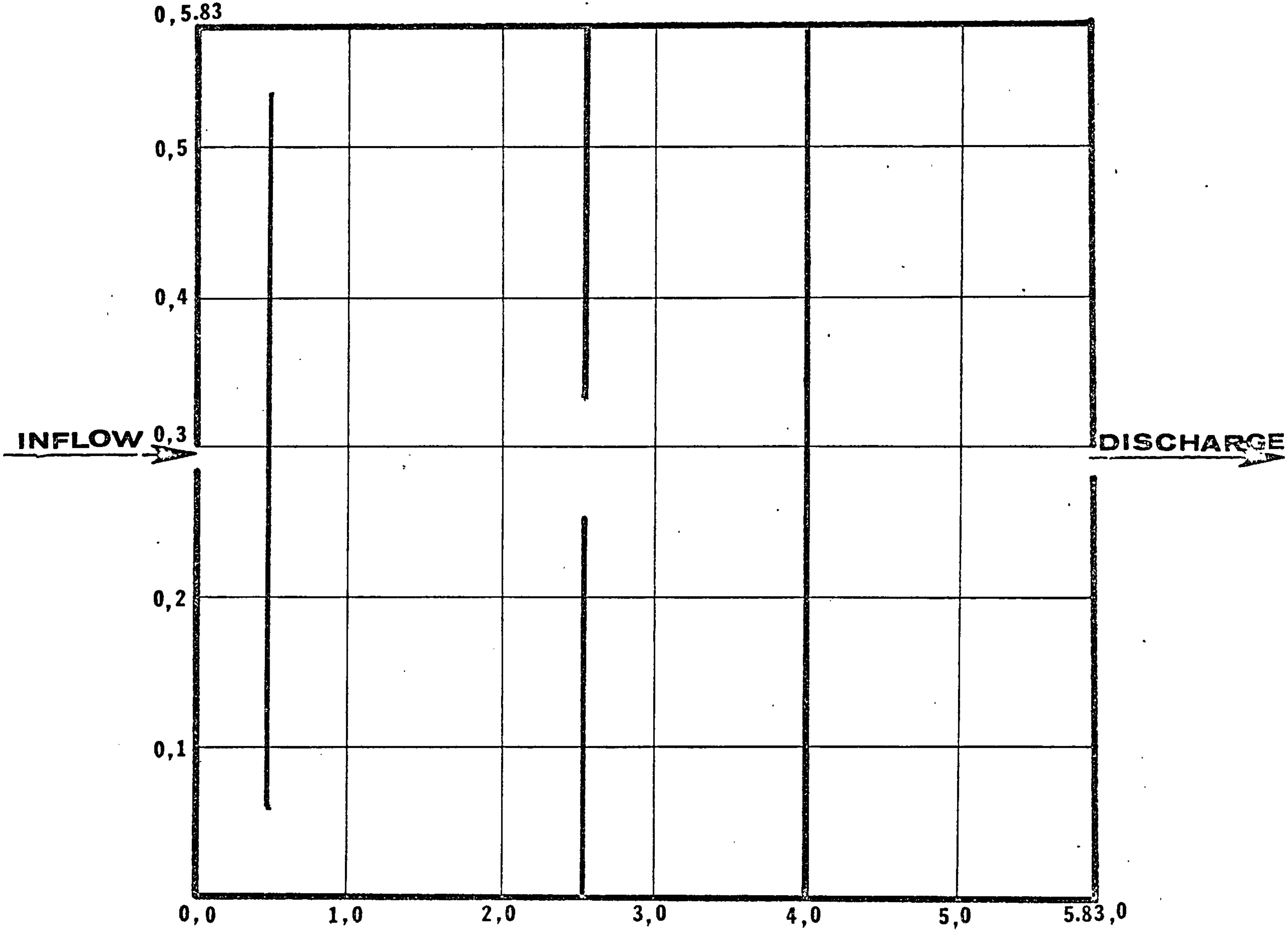
EXPERIMENT II



INLINE CANALS

INVERTED WEIR SYSTEM

APPENDIX C
FIGURE C – 3
EXPERIMENT III

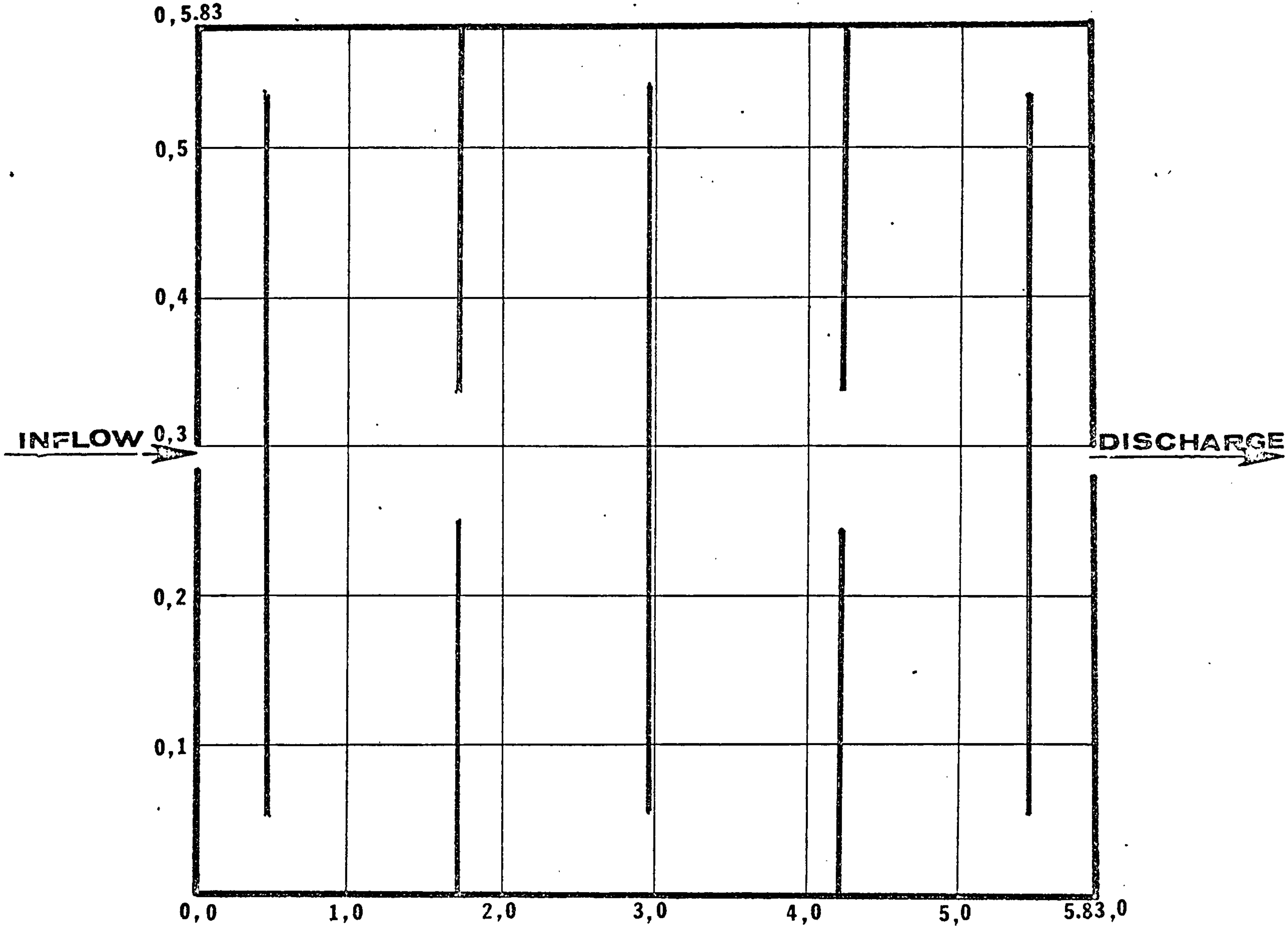


INLINE CANALS
DEFLECTION SYSTEM
WITH INVERTED WEIR

APPENDIX C

FIGURE C-4

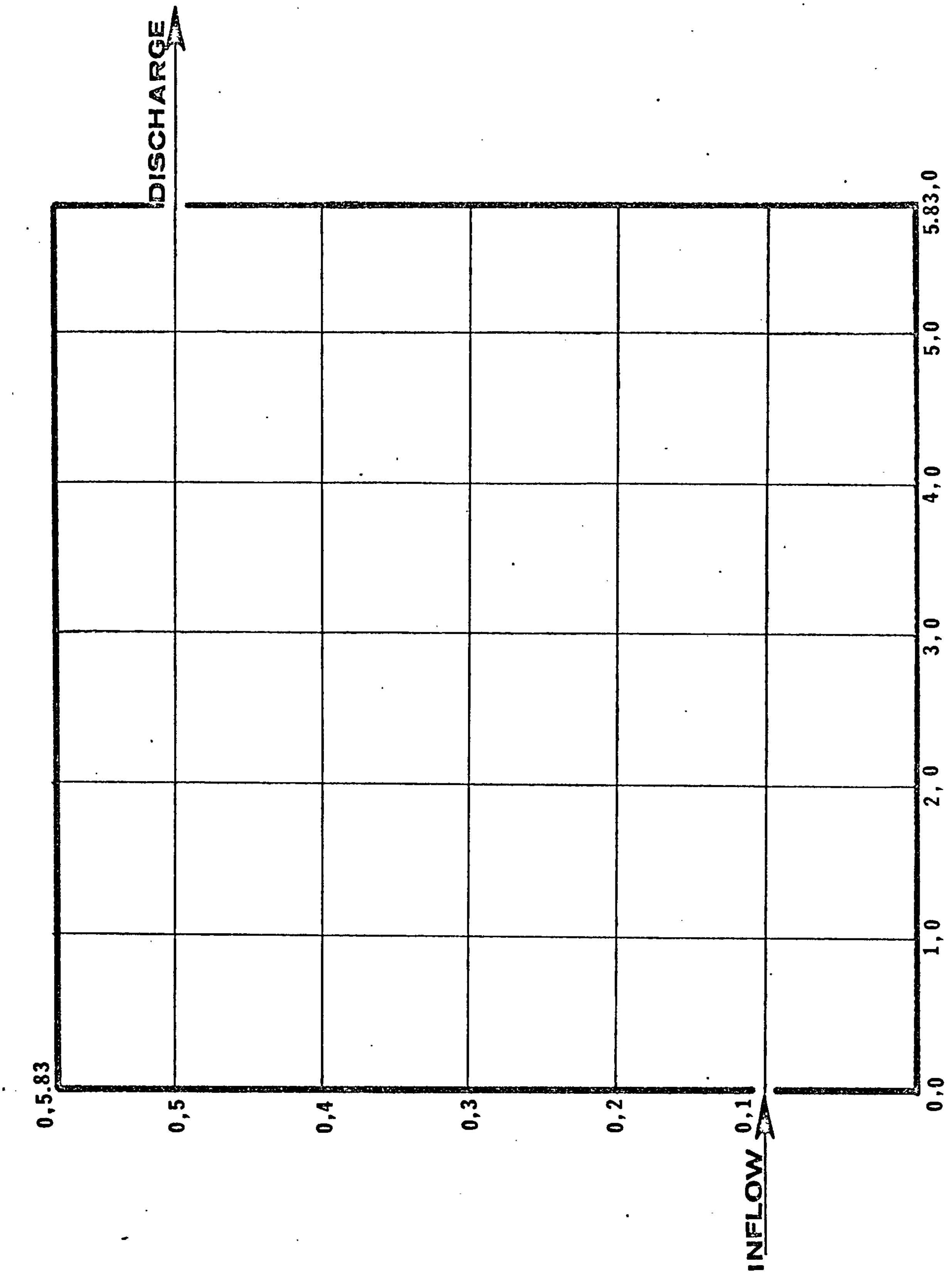
EXPERIMENT IV



INLINE CANALS

FULL DEFLECTION SYSTEM

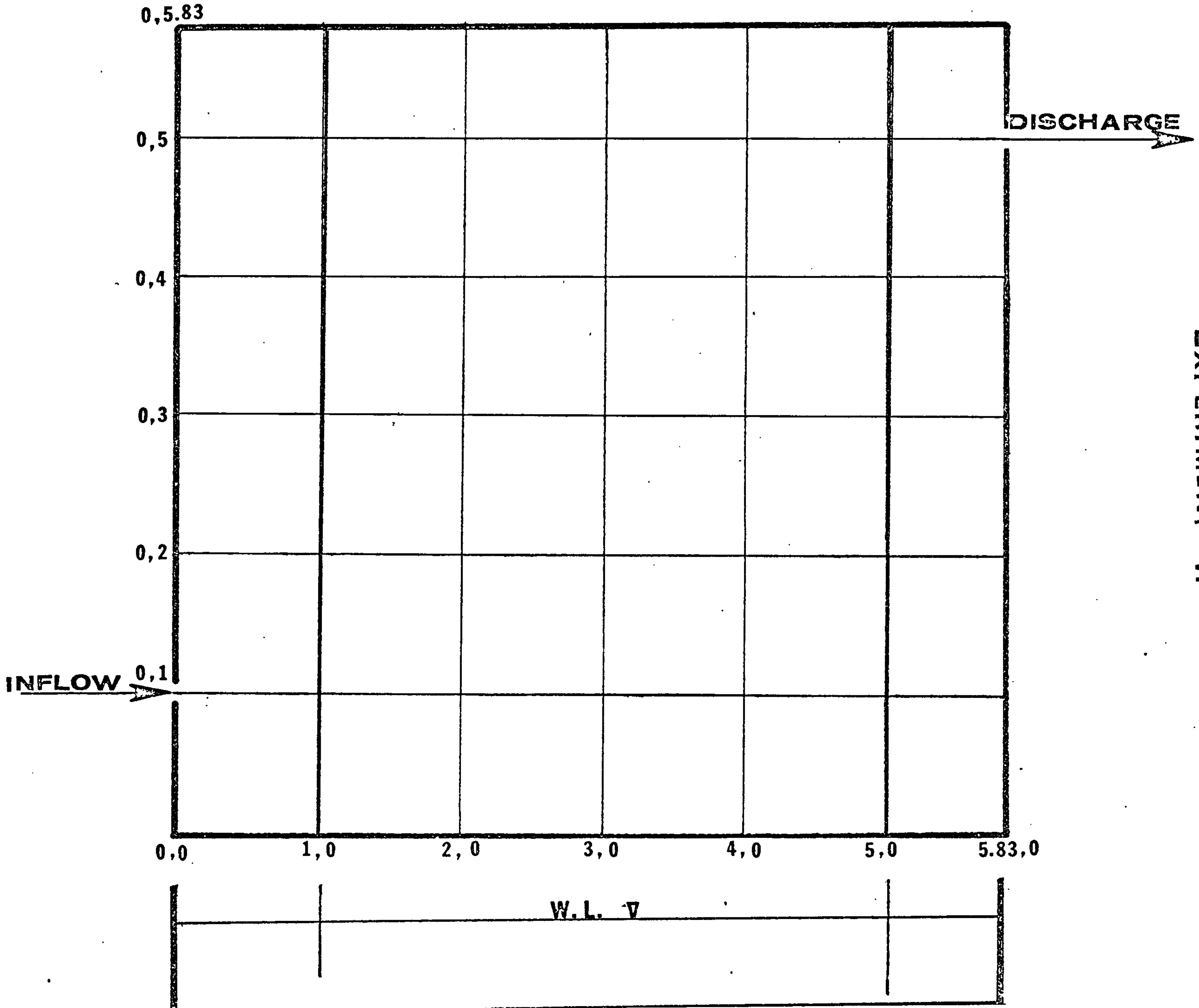
APPENDIX C
FIGURE C-5
EXPERIMENT V



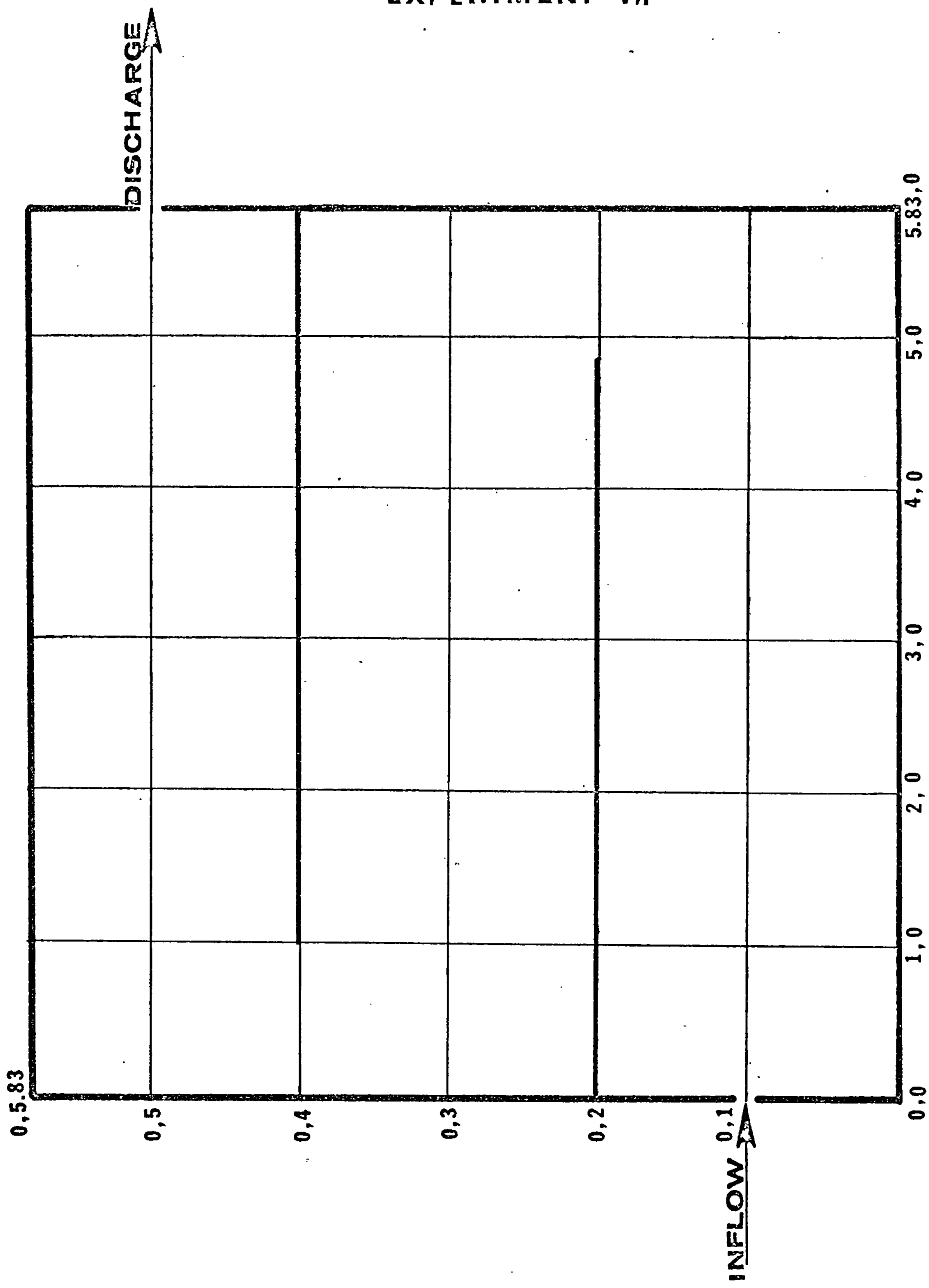
OFFSET CANALS
NO DEFLECTION SYSTEM

APPENDIX C
FIGURE C-6
EXPERIMENT VI

OFFSET CANALS
INVERTED WEIR SYSTEM

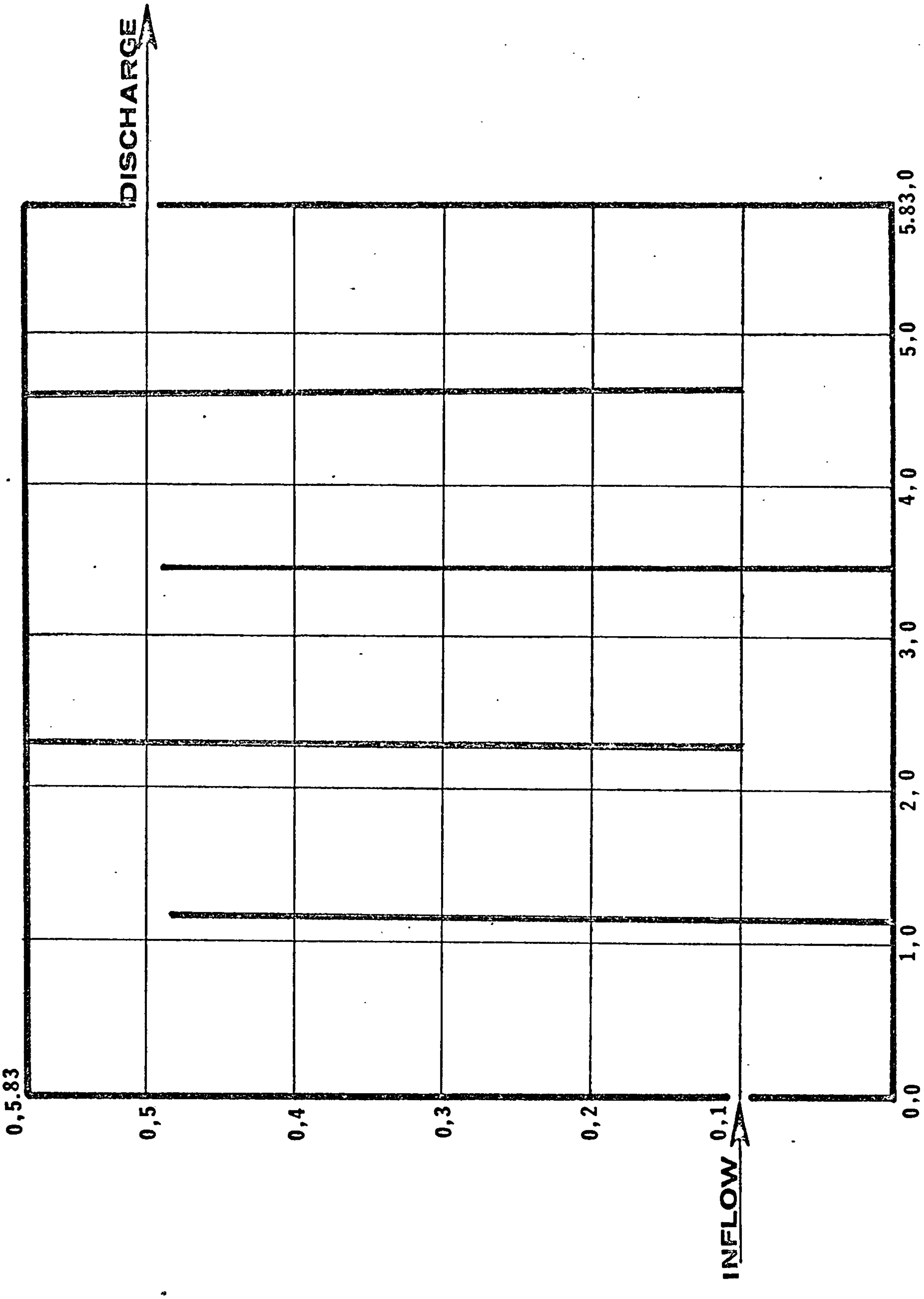


APPENDIX C
FIGURE C-7
EXPERIMENT VII



OFFSET CANALS
VERTICAL CHANNEL DEFLECTION SYSTEM

APPENDIX C
FIGURE C – 8
EXPERIMENT VIII



OFFSET CANALS

HORIZONTAL CHANNEL DEFLECTION SYSTEM

APPENDIX D

TABULATION

TEST DATA AND RESULTS

APPENDIX D

TABLE 2

EXPERIMENT # I

TEST # 1

WET BULB 72 °F DRY BULB 76 °F VAPOR PRESSURE .37PSI

SURFACE VELOCITY TEST					
MODEL COORDINATES START	MODEL COORDINATES END	DISTANCE (FT)	TIME LAPSE(SEC)	SEGMENT VEL(FT/SEC)	OVERALL VEL(FT/SEC)
0,3	1,3	1.0	32	0.03	--
1,3	3,3	2.0	10	0.2	--
0,3	3,3	3.0	42	--	.07
0,3	5.83,3	5.83	60	--	.09
1,5	2,4	1	49	.02	--
1,1	4,3	3.5	18	0.1	--

SUBSURFACE VELOCITY TEST					
MODEL COORDINATES START	MODEL COORDINATES END	DISTANCE (FT)	TIME LAPSE(SEC)	SEGMENT VEL(FT/SEC)	OVERALL VEL(FT/SEC)
1,3	3,3	2	6.5	0.31	--
3,3	5,3	2.	10.	0.2	--
1,3	5,3	4	16.5	--	0.22
1,1	4,2	3.2	5 2	0.06	--
1,5	1,4	1	16	0.06	--
1,4	2,3	1.6	9	0.2	--
1,5	2,3	2.6	25	--	0.1
2,3	4,3	2	32	0.06	--
1,5	4,3	4.6	57	--	0.08

TEMPERATURE TEST			
INFLOW TEMPERATURE	106.2°F		
INTERMEDIATE COORDINATES	---		
TEMPERATURE READING	---		
OUTFLOW TEMPERATURE	105.5°F		ΔT= 0.7 °F
RESIDENCE TIME	MODEL 28 (SEC)	PROTOTYPE .08 (DAY)	
		POND EFFICIENCY	2.2 %

APPENDIX D

TABLE 3

EXPERIMENT # I

TEST # 2

WET BULB 73 °F DRY BULB 75 °F VAPOR PRESSURE .39PSI

SURFACE VELOCITY TEST

MODEL COORDINATES START	MODEL COORDINATES END	DISTANCE (FT)	TIME LAPSE(SEC)	SEGMENT VEL(FT/SEC)	OVERALL VEL(FT/SEC)
0,3	2,3	2	20	0.1	--
1,1	3,2.5	2.5	34	.07	
3,2.5	5,3	2	24	.08	
1,1	5,3	4.5	58		.08

SUBSURFACE VELOCITY TEST

MODEL COORDINATES START	MODEL COORDINATES END	DISTANCE (FT)	TIME LAPSE(SEC)	SEGMENT VEL(FT/SEC)	OVERALL VEL(FT/SEC)
1,3	3,3	2	18	.1	
3,3	4,3	1	10	.1	
1,3	4,3	3	28	--	.1
1,5	2,3	2.4	30	.08	
2,1	4,3.5	2	29	.07	

TEMPERATURE TEST

INFLOW TEMPERATURE	106.0 °F		
INTERMEDIATE COORDINATES	--		
TEMPERATURE READING	--		
OUTFLOW TEMPERATURE	105.7 °F		ΔT= 0.3 °F
RESIDENCE TIME	MODEL 27 (SEC)	PROTOTYPE .079 (DAY)	
	POND EFFICIENCY		2.2 %

APPENDIX D

TABLE 4

EXPERIMENT # II

TEST # 1

WET BULB 72 °F   DRY BULB 78 °F   VAPOR PRESSURE .36 PSI

SURFACE VELOCITY TEST

MODEL COORDINATES START	MODEL COORDINATES END	DISTANCE (FT)	TIME LAPSE (SEC)	SEGMENT VEL (FT/SEC)	OVERALL VEL (FT/SEC)
	NO	SURFACE VELOCITY TESTS			

SUBSURFACE VELOCITY TEST

MODEL COORDINATES START	MODEL COORDINATES END	DISTANCE (FT)	TIME LAPSE (SEC)	SEGMENT VEL (FT/SEC)	OVERALL VEL (FT/SEC)
1.5,3	4,3	2.5	13	0.2	
4,3	5,3	1	16	0.06	
1.5,3	5,3	3.5	29	--	0.1
5,3	5.83,3	0.8	47	.01	
1.5,3	5.83,3	4.3	76		.05
1,1	4,3	4.5	87	.05	
0,3	4,3	4	58	0.07	

TEMPERATURE TEST

INFLOW TEMPERATURE	110.0 °F		
INTERMEDIATE COORDINATES	--		
TEMPERATURE READING	--		
OUTFLOW TEMPERATURE	109.4 °F	ΔT= 0.6 °F	
RESIDENCE TIME	MODEL 127 (SEC)	PROTOTYPE .37 (DAY)	
	POND EFFICIENCY	10.1 %	

APPENDIX D

TABLE 5

EXPERIMENT # II

TEST # 2

WET BULB 71 °F   DRY BULB 75 °F   VAPOR PRESSURE .35 PSI

SURFACE VELOCITY TEST

MODEL COORDINATES START	MODEL COORDINATES END	DISTANCE (FT)	TIME LAPSE(SEC)	SEGMENT VEL(FT/SEC)	OVERALL VEL(FT/SEC)
		NO SURFACE	VELOCITY	TESTS	

SUBSURFACE VELOCITY TEST

MODEL COORDINATES START	MODEL COORDINATES END	DISTANCE (FT)	TIME LAPSE(SEC)	SEGMENT VEL(FT/SEC)	OVERALL VEL(FT/SEC)
1,3	3.3	2	12	0.2	
3,3	4.5,3	1.5	20	0.08	
1,3	4.5,3	3.5	32	--	0.1
1,2	3.5,2	2.5	42	0.06	
0.5,5	3,4	2.5	62	0.04	
3,4	5.83,3	3.5	76	0.05	
0.5,5	5.83,3	6.0	132	--	.04

TEMPERATURE TEST

INFLOW TEMPERATURE	106.5 °F		
INTERMEDIATE COORDINATES			
TEMPERATURE READING			
OUTFLOW TEMPERATURE	106 °F	ΔT= 0.5 °F	
RESIDENCE TIME	MODEL 130 (SEC)	PROTOTYPE .38 (DAY)	
	POND EFFICIENCY	10.3 %	

APPENDIX D

TABLE 6

EXPERIMENT # III

TEST # 1

WET BULB 72 °F   DRY BULB 78 °F   VAPOR PRESSURE .36 PSI

SURFACE VELOCITY TEST					
MODEL COORDINATES START	MODEL COORDINATES END	DISTANCE (FT)	TIME LAPSE (SEC)	SEGMENT VEL (FT/SEC)	OVERALL VEL (FT/SEC)
0,3.5	0,5	1.5	35	0.04	--
1,5	1,5	0	17	0	--
0,2.5	0.5,0.5	2.2	47	0.05	--

SUBSURFACE VELOCITY TEST					
MODEL COORDINATES START	MODEL COORDINATES END	DISTANCE (FT)	TIME LAPSE (SEC)	SEGMENT VEL (FT/SEC)	OVERALL VEL (FT/SEC)
0,2.5	1,0	2.9	24	0.1	
0,3.5	0,5	1.5	32	0.05	
2.5,3	4,3	1.5	38	0.04	
4,3	5.83,3	1.83	79	0.02	
2.5,3	5.83,3	3.[illegible]	117	--	.03
3,5	3.5	0	15	0	
5,1	5,1	0	17	0	

TEMPERATURE TEST			
INFLOW TEMPERATURE	106.8 °F		
INTERMEDIATE COORDINATES	--		
TEMPERATURE READING	--		
OUTFLOW TEMPERATURE	106.0 °F	ΔT= .8 °F	
RESIDENCE TIME	MODEL 188 (SEC)	PROTOTYPE .55 (DAY)	
	POND EFFICIENCY	15 %	

APPENDIX D

TABLE 7

EXPERIMENT # III

TEST # 2

WET BULB 70 °F   DRY BULB 74 °F   VAPOR PRESSURE 34 PSI

SURFACE VELOCITY TEST

MODEL COORDINATES START	MODEL COORDINATES END	DISTANCE (FT)	TIME LAPSE(SEC)	SEGMENT VEL(FT/SEC)	OVERALL VEL(FT/SEC)
0.5,5	1.5,5	1.5	42	0.04	--
2.1	2,2.5	1.5	39	0.04	--
2.5,3	3.5,3	1	42	0.02	--

SUBSURFACE VELOCITY TEST

MODEL COORDINATES START	MODEL COORDINATES END	DISTANCE (FT)	TIME LAPSE(SEC)	SEGMENT VEL(FT/SEC)	OVERALL VEL(FT/SEC)
0,2	1,0.5	2	20	0.1	
2,0	2,2	2	32	0.06	
4,3	5.83,3	1.8	41	0.05	

TEMPERATURE TEST

INFLOW TEMPERATURE	104.2 °F		
INTERMEDIATE COORDINATES	--		
TEMPERATURE READING	--		
OUTFLOW TEMPERATURE	103.5 °F		ΔT= 0.7 °F
RESIDENCE TIME	MODEL 190 (SEC)	PROTOTYPE .56 (DAY)	
	POND EFFICIENCY		15.1 %

APPENDIX D

TABLE 8

EXPERIMENT # IV

TEST # 1

WET BULB 68 °F   DRY BULB 73 °F   VAPOR PRESSURE .31 PSI

SURFACE VELOCITY TEST

MODEL COORDINATES START	MODEL COORDINATES END	DISTANCE (FT)	TIME LAPSE(SEC)	SEGMENT VEL(FT/SEC)	OVERALL VEL(FT/SEC)
0,3	0.5,5.6	2.7	60	0.05	
1,1	1,1	0	15	0	
1.5,1	2,2.5	1.7	68	0.02	
2,2.5	2.75,0.3	2	62	0.04	
1.5,1	2.75,0.3	3.9	130	--	0.03

SUBSURFACE VELOCITY TEST

MODEL COORDINATES START	MODEL COORDINATES END	DISTANCE (FT)	TIME LAPSE(SEC)	SEGMENT VEL(FT/SEC)	OVERALL VEL(FT/SEC)
1,1	2,2.5	1.6	35	0.05	
2.8,0.5	4,1	1.7	75	0.02	
4,3	5,5	2.3	69	0.03	
4,3	5,1	2.3	75	0.03	

TEMPERATURE TEST

INFLOW TEMPERATURE	101.8 °F		
INTERMEDIATE COORDINATES	0.5,5.83	2,3	4,3
TEMPERATURE READING	101.8	101.7	101.5
OUTFLOW TEMPERATURE	100.5 °F		ΔT= 1.3 °F
RESIDENCE TIME	MODEL 910 (SEC)	PROTOTYPE 2.66 (DAY)	
	POND EFFICIENCY	72.5 %	

APPENDIX D

TABLE 9

EXPERIMENT # IV

TEST # 2

WET BULB 70 °F DRY BULB 74 °F VAPOR PRESSURE .34 PSI

SURFACE VELOCITY TEST

MODEL COORDINATES START	MODEL COORDINATES END	DISTANCE (FT)	TIME LAPSE (SEC)	SEGMENT VEL (FT/SEC)	OVERALL VEL (FT/SEC)
0,4	1,5	2.4	70	0.03	
1.5,3	2.5,4	1.9	63	0.03	
3.5,2	4.5,3	1.4	60	0.02	

SUBSURFACE VELOCITY TEST

MODEL COORDINATES START	MODEL COORDINATES END	DISTANCE (FT)	TIME LAPSE (SEC)	SEGMENT VEL (FT/SEC)	OVERALL VEL (FT/SEC)
0.5,0.5	1.5,2	2	35	0.06	
2,2	0.5,3	1.5	40	0.04	
4,3	5,5	2.3	73	0.03	

TEMPERATURE TEST

INFLOW TEMPERATURE	103.6 °F		
INTERMEDIATE COORDINATES	2,3	3.4	
TEMPERATURE READING	103.4	103.0	
OUTFLOW TEMPERATURE	102.4 °F		ΔT= 1.2 °F
RESIDENCE TIME	MODEL 923 (SEC)	PROTOTYPE 2.7 (DAY)	
	POND EFFICIENCY	73.5 %	

APPENDIX D

TABLE 10

EXPERIMENT # V

TEST # 1

WET BULB 72 °F DRY BULB 76 °F VAPOR PRESSURE .37PSI

SURFACE VELOCITY TEST					
MODEL COORDINATES START	MODEL COORDINATES END	DISTANCE (FT)	TIME LAPSE(SEC)	SEGMENT VEL(FT/SEC)	OVERALL VEL(FT/SEC)
1,1	4,1	3	34	0.09	
1,1	4,2.5	4	63	0.06	
5,2	1,4	4	40	0.09	
4,5	2,4	2.5	43	0.06	

SUBSURFACE VELOCITY TEST					
MODEL COORDINATES START	MODEL COORDINATES END	DISTANCE (FT)	TIME LAPSE(SEC)	SEGMENT VEL(FT/SEC)	OVERALL VEL(FT/SEC)
1,1	5,1	4	35	0.1	
1,5	1,2	3	39	0.08	
4,4	2.5,2.5	3.5	52	0.07	

TEMPERATURE TEST			
INFLOW TEMPERATURE	103.9 °F		
INTERMEDIATE COORDINATES	--		
TEMPERATURE READING	--		
OUTFLOW TEMPERATURE	103.7 °F		ΔT=0.2 °F
RESIDENCE TIME	MODEL 54 (SEC)	PROTOTYPE	.16 (DAY)
		POND EFFICIENCY	4.3 %

APPENDIX D

TABLE 11

EXPERIMENT # V

TEST # 2

WET BULB 70 °F   DRY BULB 75 °F   VAPOR PRESSURE .33 PSI

SURFACE VELOCITY TEST

MODEL COORDINATES START	MODEL COORDINATES END	DISTANCE (FT)	TIME LAPSE (SEC)	SEGMENT VEL (FT/SEC)	OVERALL VEL (FT/SEC)
1,1	5,2	4.2	40	0.1	
4,1	5,3	2.2	30	0.07	
4,3	4.5,4	1	40	0.03	
4.5,4	2,5	2.8	35	0.06	
4,3	2,5	3.8	75	--	0.05

SUBSURFACE VELOCITY TEST

MODEL COORDINATES START	MODEL COORDINATES END	DISTANCE (FT)	TIME LAPSE (SEC)	SEGMENT VEL (FT/SEC)	OVERALL VEL (FT/SEC)
2,1	4.5,2.5	3.2	33	0.1	
1,3	2,1	2.4	40	0.06	
4,3	5.5,4	1.9	51	0.04	

TEMPERATURE TEST

INFLOW TEMPERATURE	101.3 °F		
INTERMEDIATE COORDINATES	3,3		
TEMPERATURE READING	101		
OUTFLOW TEMPERATURE	100.8 °F		ΔT= 0.5 °F
RESIDENCE TIME	MODEL 52 (SEC)	PROTOTYPE .15 (DAY)	
	POND EFFICIENCY		4.1 %

APPENDIX D

TABLE 12

EXPERIMENT # VI

TEST # 1

WET BULB 72 °F DRY BULB 76 °F VAPOR PRESSURE .77PSI

SURFACE VELOCITY TEST						
MODEL COORDINATES START	MODEL COORDINATES END	DISTANCE (FT)	TIME LAPSE(SEC)	SEGMENT VEL(FT/SEC)	OVERALL VEL(FT/SEC)
		NO SURFACE	VELOCITY	TESTS	

SUBSURFACE VELOCITY TEST					
MODEL COORDINATES START	MODEL COORDINATES END	DISTANCE (FT)	TIME LAPSE(SEC)	SEGMENT VEL(FT/SEC)	OVERALL VEL(FT/SEC)
1,1	3.1	2	35	0.06	
3,1	4,1.5	1.5	86	0.02	
1,1	4,1.5	3.5	121	--	0.03
4,1.5	5.83,5	4	174	0.02	
1,1	5.83,5	7	295	--	0.02
2,5	5,4.5	3	147	0.02	
5,4.5	5.83,5	1	40	0.03	
2,5	5.83,5	4	187	--	0.02

TEMPERATURE TEST				
INFLOW TEMPERATURE	102.4 °F			
INTERMEDIATE COORDINATES	5.83,3	4,4		
TEMPERATURE READING	101.8	102		
OUTFLOW TEMPERATURE	101.6 °F		ΔT= 0.8 °F	
RESIDENCE TIME	MODEL 323 (SEC)	PROTOTYPE .95 (DAY)		
	POND EFFICIENCY		25.7 %	

APPENDIX D

TABLE 13

EXPERIMENT # VI

TEST # 2

WET BULB 72 °F   DRY BULB 76 °F   VAPOR PRESSURE .37 PSI

SURFACE VELOCITY TEST

MODEL COORDINATES START	MODEL COORDINATES END	DISTANCE (FT)	TIME LAPSE (SEC)	SEGMENT VEL (FT/SEC)	OVERALL VEL (FT/SEC)
	NO	SURFACE	VELOCITY	TESTS	

SUBSURFACE VELOCITY TEST

MODEL COORDINATES START	MODEL COORDINATES END	DISTANCE (FT)	TIME LAPSE (SEC)	SEGMENT VEL (FT/SEC)	OVERALL VEL (FT/SEC)
1,1.5	3,2	1.75	38	0.05	
1,4	1,4	0	30	0	
2,2	4,3	2.2	94	0.02	
4,3	5.83,5	3	112	0.03	
2,2	5.83,5	5.2	206	--	0.02

TEMPERATURE TEST

INFLOW TEMPERATURE	109.4 °F		
INTERMEDIATE COORDINATES	3,2	4,3 MW	4,3 BOT.
TEMPERATURE READING	109.2	108.8	108.6
OUTFLOW TEMPERATURE	108.5 °F		ΔT= 0.9 °F
RESIDENCE TIME	MODEL 320 (SEC)	PROTOTYPE .94 (DAY)	
	POND EFFICIENCY	25.5 %	

APPENDIX D

TABLE 14

EXPERIMENT # VII

TEST # 1

WET BULB 74 °F   DRY BULB 78 °F   VAPOR PRESSURE .39 PSI

SURFACE VELOCITY TEST

MODEL COORDINATES START	MODEL COORDINATES END	DISTANCE (FT)	TIME LAPSE (SEC)	SEGMENT VEL (FT/SEC)	OVERALL VEL (FT/SEC)
1,1	1,1.5	0.5	92	0	
5,1	5,1	0	15	0	
5.5,2	5.83,3	1	55	0.02	
5.5,2	5.5,3.5	1.8	172	0.01	
0.5,4	0.5,5	1	62	0.02	
3,5	4,5	1	90	0.01	

SUBSURFACE VELOCITY TEST

MODEL COORDINATES START	MODEL COORDINATES END	DISTANCE (FT)	TIME LAPSE (SEC)	SEGMENT VEL (FT/SEC)	OVERALL VEL (FT/SEC)
2,1	4,1	2	26	0.08	
5.5,2	4,3	2.6	27	0.1	
4,3	1,4	3	41	0.07	
5.5,2	1,4	5.6	68	--	0.08

TEMPERATURE TEST

INFLOW TEMPERATURE	104.0 °F		
INTERMEDIATE COORDINATES	5,1	1,5	
TEMPERATURE READING	104.0	103.2	
OUTFLOW TEMPERATURE	102.8 °F		ΔT= 1.2 °F
RESIDENCE TIME	MODEL 447 (SEC)	PROTOTYPE 1.31 (DAY)	
	POND EFFICIENCY	35.6 %	

Wetted Perimeter = 3.06 **FT.**

Hydraulic Radius = 0.35 **FT.**

Area = 1.06 **FT.**^{2}

APPENDIX D

TABLE 15

EXPERIMENT # VII

TEST # 2

WET BULB 73 °F DRY BULB 77 °F VAPOR PRESSURE .38 PSI

SURFACE VELOCITY TEST					
MODEL COORDINATES START	MODEL COORDINATES END	DISTANCE (FT)	TIME LAPSE (SEC)	SEGMENT VEL (FT/SEC)	OVERALL VEL (FT/SEC)
2,1.5	4,1.5	2	61	0.03	
4.5,3	2,3.5	2.7	79	0.03	
1,2.5	0.5,4	1.5	80	0.02	
3,5	5,5	2	124	0.02	

SUBSURFACE VELOCITY TEST					
MODEL COORDINATES START	MODEL COORDINATES END	DISTANCE (FT)	TIME LAPSE (SEC)	SEGMENT VEL (FT/SEC)	OVERALL VEL (FT/SEC)
2,1	4,1	2	30	0.05	
4,3	2,3	2	27	0.07	
2,5	4,5	2	60	0.03	

TEMPERATURE TEST			
INFLOW TEMPERATURE	106.2°F		
INTERMEDIATE COORDINATES	5,3	0.5,4	
TEMPERATURE READING	106.1	105.7	
OUTFLOW TEMPERATURE	105.3°F		ΔT= 0.9 °F
RESIDENCE TIME	MODEL 435 (SEC)	PROTOTYPE 1.27 (DAY)	
	POND EFFICIENCY	34.7 %	

Wetted Perimeter = 3.06 **FT**
Hydraulic Radius = 0.35 **FT**
Area = 1.06 **FT**^{2}

APPENDIX D

TABLE 16

EXPERIMENT # VIII

TEST # 1

WET BULB 74 °F   DRY BULB 78 °F   VAPOR PRESSURE .39 PSI

SURFACE VELOCITY TEST

MODEL COORDINATES START	MODEL COORDINATES END	DISTANCE (FT)	TIME LAPSE (SEC)	SEGMENT VEL (FT/SEC)	OVERALL VEL (FT/SEC)
0.5,2	0.5,2	0	15	0	
0.5,4	0.5,4	0	17	0	
1,5.2	2,4	1.6	43	0.04	
4.5,4	4.5,2	2	43	0.05	

SUBSURFACE VELOCITY TEST

MODEL COORDINATES START	MODEL COORDINATES END	DISTANCE (FT)	TIME LAPSE (SEC)	SEGMENT VEL (FT/SEC)	OVERALL VEL (FT/SEC)
0.5,2	0.5,4	2	46	0.04	
1,5,4	2,3	1	65	0.02	
4,5	4,3	2	63	0.03	
5,2	5,4	2	52	0.04	

TEMPERATURE TEST

INFLOW TEMPERATURE	102.2 °F			
INTERMEDIATE COORDINATES	0.5,5	2,3	3,3	4.2
TEMPERATURE READING	102.2	102.2	101.8	101.7
OUTFLOW TEMPERATURE	101.0 °F			ΔT=1.2 °F
RESIDENCE TIME	MODEL 1097 (SEC)	PROTOTYPE 3.21 (DAY)		
	POND EFFICIENCY			87.1 %

Wetted Perimeter = 2.24 FT
Hydraulic Radius = 0.78 FT
Area = 0.625 FT^2

APPENDIX D

TABLE 17

EXPERIMENT # VIII

TEST # 2

WET BULB 73 °F   DRY BULB 77 °F   VAPOR PRESSURE .38 PSI

SURFACE VELOCITY TEST

MODEL COORDINATES START	MODEL COORDINATES END	DISTANCE (FT)	TIME LAPSE (SEC)	SEGMENT VEL (FT/SEC)	OVERALL VEL (FT/SEC)
0.5,2	1,4	2	67	0.03	
1.5,3	2,0.5	2.8	97	0.03	
3.5,5	4,4	2	203	0.01	

SUBSURFACE VELOCITY TEST

MODEL COORDINATES START	MODEL COORDINATES END	DISTANCE (FT)	TIME LAPSE (SEC)	SEGMENT VEL (FT/SEC)	OVERALL VEL (FT/SEC)
0.5,3	5,1	2	50	0.04	
2,2	3,1	1.9	60	0.03	
4,4	4.5,2	2.4	72	0.03	

TEMPERATURE TEST

INFLOW TEMPERATURE	106.3 °F		
INTERMEDIATE COORDINATES	2,2	3,5	5,1
TEMPERATURE READING	106.2	105.9	105.5
OUTFLOW TEMPERATURE	104.9 °F		ΔT= 1.4 °F
RESIDENCE TIME	MODEL 1103 (SEC)	PROTOTYPE 3.23 (DAY)	
	POND EFFICIENCY	38.3 %	

Wetted Perimeter = 2.24 FT
Hydraulic Radius = 0.625 FT
Area = 0.28 FT^2

APPENDIX E

EQUATION UNIT VERIFICATION

EQUATION 1

$$Q_s = BTU/FT^2/HR$$

$$Q_r = BTU/FT^2/HR$$

$$C = \text{No Units - Reflectivity}$$

$$Q_i = (1-0.0071C^2)\ (Q_s - Q_r)$$

$$BTU/FT^2/HR = \text{Constant}\ (BTU/FT^2/HR - BTU/FT^2/HR)$$

$$BTU/FT^2/HR = BTU/FT^2/HR - BTU/FT^2/HR$$

EQUATION 2

$$Q_a = BTU/FT^2/HR$$

$$T_6 = {}^oF$$

$$\beta = \text{No Units - Radiation Factor}$$

$$\nabla = BTU/FT^2/HR/{}^oR^4$$

$$Q_a = \nabla(T_6 + 460)^4 \beta$$

$$= (BTU/FT^2/HR/{}^oR^4)\ ({}^oF + 460)^4\ (\text{Constant})$$

$$BTU/FT^2/HR = (BTU/FT^2/HR/{}^oR^4)\ ({}^oR^4)\ (\text{Constant})$$

EQUATION 3

$$Q_{br} = BTU/FT^2/HR$$

$$\gamma w = \text{No Units - Emissivity}$$

$$\nabla = BTU/FT^2/HR/{}^oR^4$$

$$Tw = {}^oF$$

$$Q_{br} = \gamma w\ \nabla(T_w + 460)^4$$

EQUATION 3 (cont.)

$$= (\text{Constant})\ (BTU/FT^2/HR/{}^{\circ}R^4)\ ({}^{\circ}F + 460^4)$$

$$BTU/FT^2/HR = (BTU/FT^2/HR/{}^{\circ}R^4)\ ({}^{\circ}R^4)$$

EQUATION 4

$$U = \text{Knots}$$

$$e_a = e_w = MM\ H_g;\ .491\ LB/IN^2 = 1IN.\ H_g = 45.72\ MM\ H_g$$

$$1.151\ MPH = 1\ \text{Knot}$$

$$778.26\ FT\ LB = 1\ BTU$$

$$Q_e = 12\ U\ (e_w - e_a)$$

$$(\text{Knot})\ (M/H\ \text{Knot})\ (FT/M)\ (LB/IN^2)\ \left(\frac{IN^2}{FT^2}\right)\ \left(\frac{1}{FT\ LB/BTU}\right)$$

$$Q_e = BTU/FT^2/HR = BTU/FT^2/HR$$

EQUATION 5

From Review of Bowens Ratio

$$B = C\ \left(\frac{T_w - T_a}{e_w - e_a}\right)\quad P = Q_c/Q_e$$

Where C is a constant that is temperature dependent

By substitution of equation 4

$$C\ (T_w - T_a)\ UP\ \text{Where}$$

$$T_w = T_a = {}^{\circ}F$$

$$P = MM\ H_g = LB/FT^2$$

$$U = \text{Knots} = 1.151\ MPH$$

$$C = \text{Value}/{}^{\circ}F$$

EQUATION 5 (cont.)

$$(M/H)\ (FT/M)\ (LB/FT^2)\ (^{\circ}F)\ (1/^{\circ}F)\ \left(\frac{1}{FT\ LB/BTU}\right)$$

$$BTU/FT^2/HR = BTU/FT^2/HR$$

EQUATION 8

L = Kilowatts (KW)

R = BTU/KW HR

$BTU/FT^2/HR = BTU/FT^2/HR$

$e_b = \%$

$e_t = \%$

$A = FT^2$

$Q_p = L \times R\ (e_b - e_t)/A$

$(KW)\ (BTU/KW\ HR)\ (\%)\ (FT^2)$

EQUATION 11

$K = BTU/FT^2/HR/^{\circ}F$

$A = FT^2$

$\rho = LB/FT^3$

$C_w = BTU/LB/^{\circ}F$

$F_p = FT^3/HR$

$r = KA/\rho C_w F_p$

$$(BTU/FT^2/HR/^{\circ}F)\ (FT^2)\ (LB/FT^3)\ (BTU/LB/^{\circ}F)\ (FT^3/HR)$$

$BTU/HR/^{\circ}F/BTU/HR/^{\circ}F$

r = No units

EQUATION 12

$$V = FT^3$$

$$F_p = FT^3/SEC$$

$$t_d = V/F_p$$

$$DAY = (FT^3)\left(\frac{1}{FT^3/SEC}\right)\left(\frac{1}{SEC/DAY}\right)$$

EQUATION 13

$$K = BTU/FT^2/HR/^{o}F$$

$$t_d = HR$$

$$\rho = LBS/FT^3$$

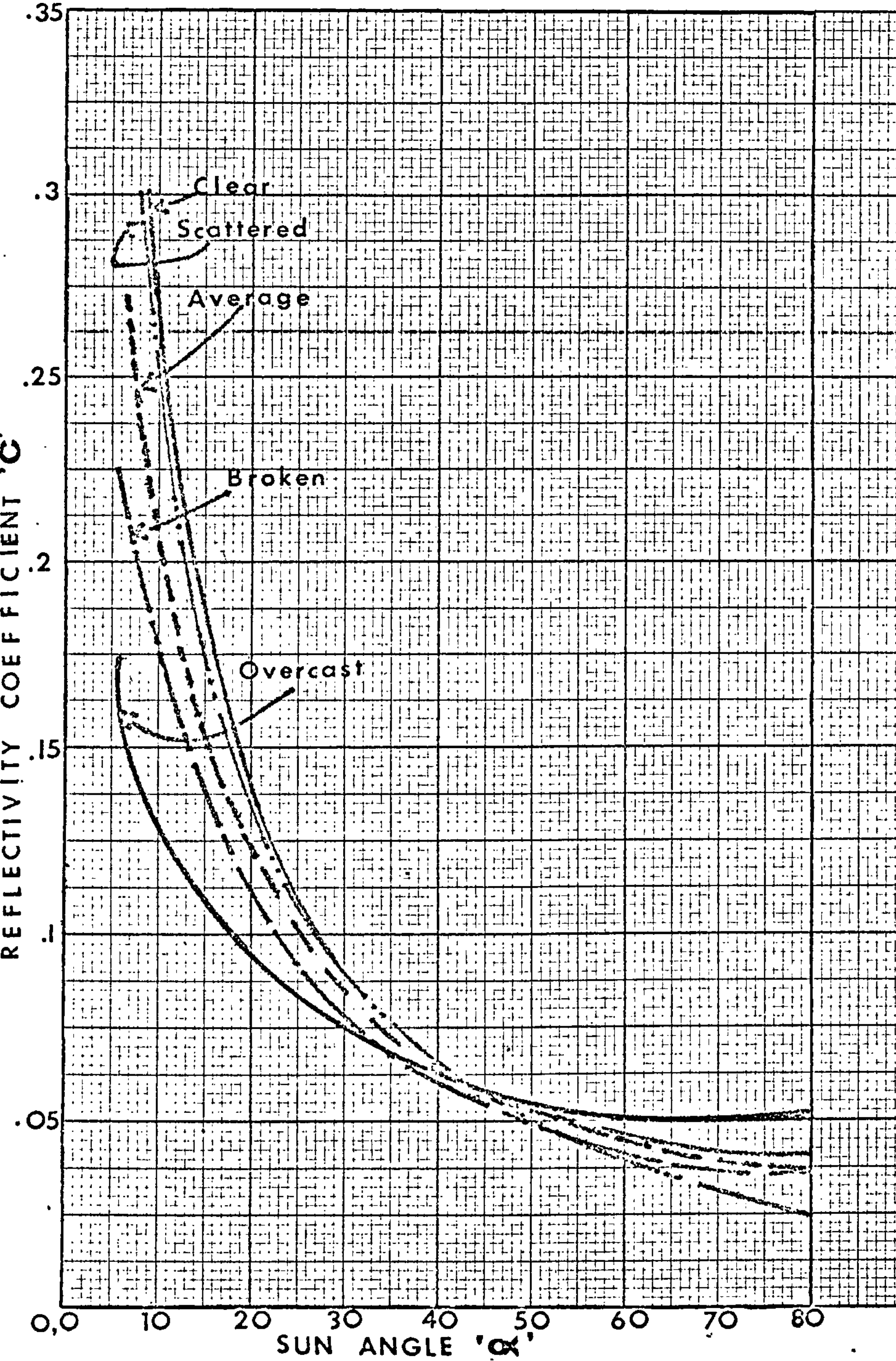
$$d = FT$$

$$r = K\, t_d/ \quad d$$

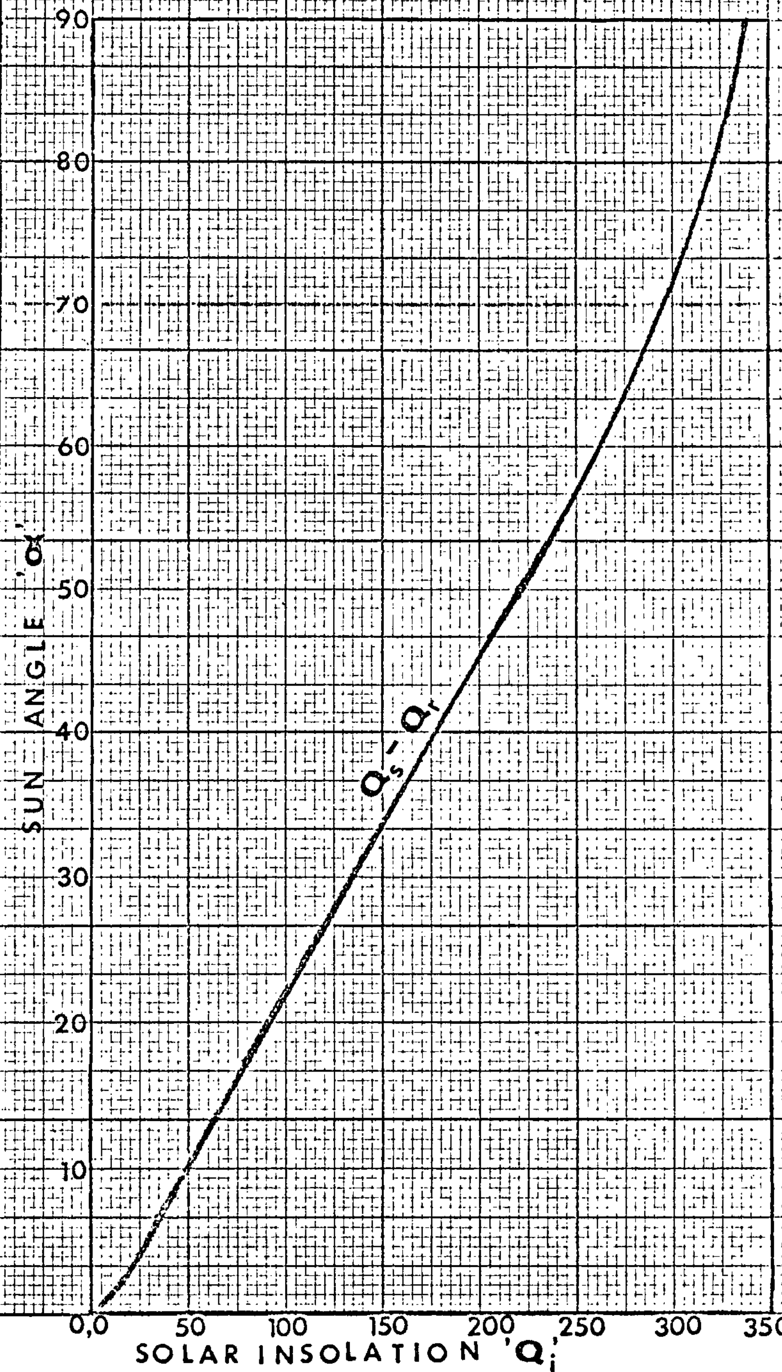
$$= (BTU/FT^2/HR/^{o}F)\ (HR)\ \left(\frac{1}{LBS/FT^3}\right)\left(\frac{1}{FT}\right)$$

$$r = BTU/LBS \quad ^{o}F$$

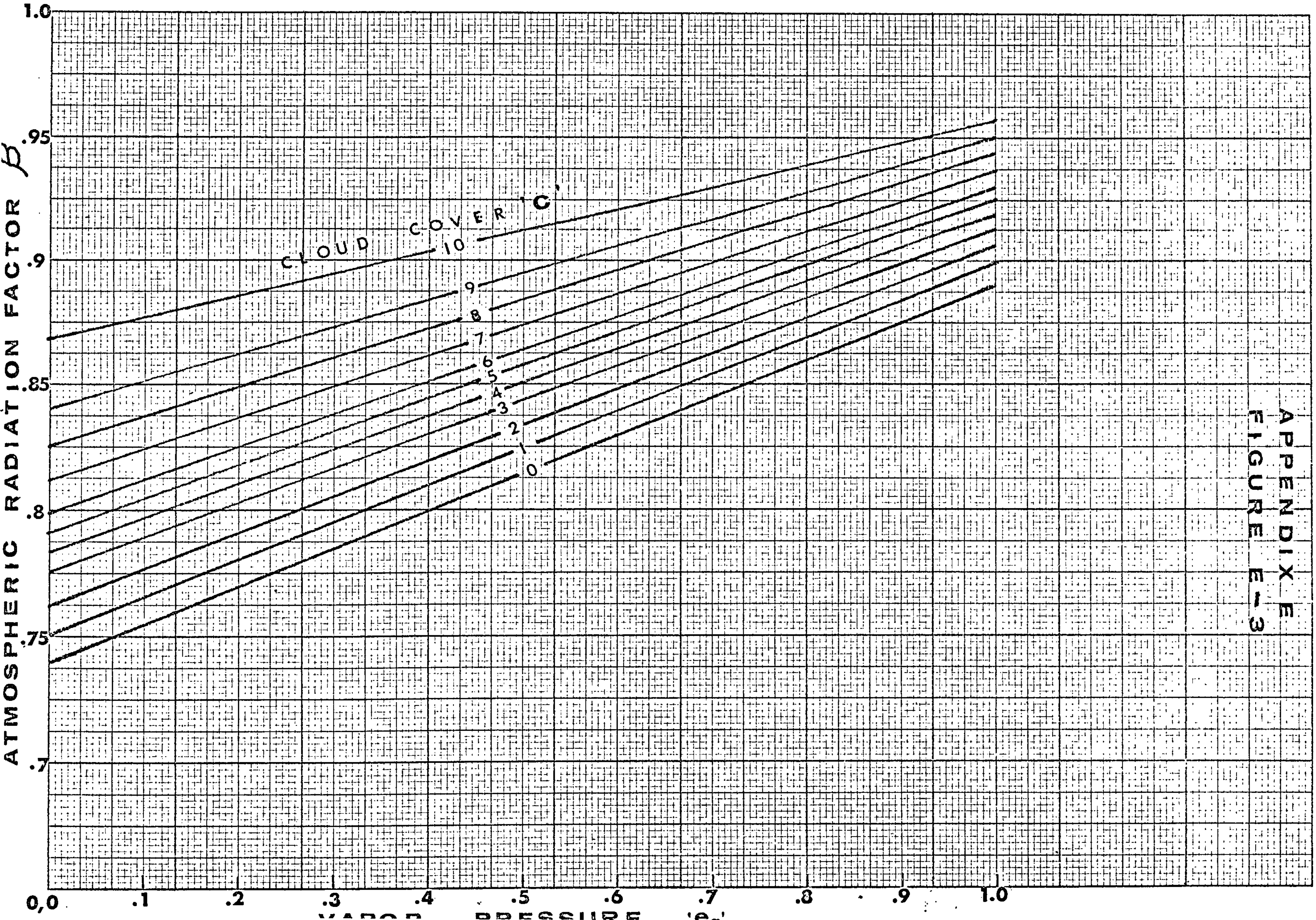
$$r = BTU/BTU \text{ No units}$$



APPENDIX E
FIGURE E-2



APPENDIX E
FIGURE E-1



APPENDIX E
FIGURE E-3

APPENDIX G

COMPUTER PROGRAM, LEAST SQUARES DATA FIT

```
      Common Y (48), X (48), N, A, B, CRC
      Write (6,8)
    8 Format (1H1, 10X, 'Coefficients are', //, 15X
     1' A', 10X, 'BX, 10X, 'Corr. Coeff.'/)
      Read (5,1) Nunits
    1 Format (I3)
      Do 50 J = 1, Nunits
      Read (5,2) Name, N
    2 Format (A4, I3)
      Read (5,3)  (Y(I), X (I), I = 1,N)
    3 Format (10F8.0)
      Call Stline
      Write (6,4)  Name, A, B, CRC
    4 Format (5X, A4, 6X, F11.7, 3X, F11.7, 3X, F11.7)
   50 Continue
      End

      Subroutine Stline
      Common Y (48), X (48), N, A, B, CRC
      SX = 0.0
      SY = 0.0
      SXY = 0.0
      SX2 = 0.0
      SY2 = 0.0
      Do 1 I = 1,N
      SX = SX + X (I)
      SY = SY + Y (I)
      SXY = SXY + X (I)* Y (I)
      SX2 = SX2 + X (I)* X (I)
      SY2 = SY2 + Y (I)* Y (I)
    1 Continue
      AN = N
      D = AN*SX2 - SX*SX
      A = (SY*SX2) /D - (SX*SXY)/D
      B = (AN*SXY)/D - (SX*SY)/D
      SSQ = 0.0
      Do 336 I = 1, N
      TEM = Y (I) - A - B * X (I)
      SSQ = SSQ + TEM*TEM
  336 Continue
      FCR = 1.0/(AN*((SY2/AN) - ((SY/AN)*(SY/AN))))
      IF (1.0 - FCR*SSQ) 401,401,437
  401 CRC = 0.0
```

```
    Go To 337
437 CRC = SQRT (1.0 - FCR*SSQ)
337 Return
    End
```

A	B	Corr. Coeff.
-0.9779987	0.3610131	0.8405227

For equation of format A + BX