EVAPORATION AND ITS SUPPRESSION WITH HEXADECANOL AND OCTADECANOL FILMS ON PAIRED PONDS AT STILLWATER, OKLAHOMA

By

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1957

Submitted to the faculty of the Graduate School of
the Oklahoma State University
in partial fulfillment of the requirements
for the degree of
MASTER OF SCIENCE
August, 1958

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PREFACE

The studies reported in this thesis are a part of a program of research on farm water supply conducted by the Oklahoma Agricultural Experiment Station. Facilities of the Evaporation Research Laboratory north of Stillwater, Oklahoma were made available for this study.

The author is grateful to Franklin R. Crow, Associate Professor of Agricultural Engineering for his inspiring council and assistance throughout the experiment and analysis of data.

Appreciation is expressed to E. W. Schroeder, Professor and Head, Department of Agricultural Engineering for his encouragement of the graduate studies of the author.

The author is grateful also to Dr. Robert D. Morrison, Associate Professor of Mathematics and Statistics, for his assistance with the statistical analysis and to the personnel of the Agricultural Engineering Department for their assistance with maintenance of facilities.

For materials furnished the author expresses thanks to the Bakelite Company, Archer-Daniels-Midland Company and the Rohm and Haas Company.

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CHAPTER I

INTRODUCTION

Evaporation losses from fresh water reservoirs used as municipal water supply and farm ponds used for household and stock water supply in many cases are several times greater than the water actually used. Such high losses contribute to the water shortage problem. Crow (4) reported the 1956 evaporation loss from Lake Carl Blackwell to be 69.4 vertical inches which was more than four times the amount withdrawn for the city of Stillwater, Oklahoma and Oklahoma A. & M. College. Tests on two farm ponds near Stillwater during July through December 1956 showed an evaporation loss of 42.39 inches compared to 3.42 inches withdrawn for household use.

Koenig (8) has estimated an evaporation loss of approximately 7.5 millions acre-feet of water per year in the state of Texas where the annual use rate is about 8 millions acre-feet. Recognizing the immensity of this loss, researchers have worked to devise methods of retarding these evaporation losses.

Windbreaks have been suggested as a method of reducing evaporation by slowing the wind and not allowing high velocities to come in contact with the water surface. Windbreaks are reported by Frevert (6, p. 131) to be effective for from 10 to 30 times the height of the structure. From model studies of Lake Hefner (3, p. 29) an area of reduced velocity was noted immediately downstream from a windbreak, but turbulence was induced beyond.

> Therefore, as a result of the presence of a barrier, two opposing effects on the wind structure are occurring simultaneously; one tends to increase the evaporation and the other tends to reduce evaporation. Data gathered . . . indicate that the two effects cancel each other.

Since evaporation occurs at the water surface, the ratio of storage capacity to surface area should be kept as large as possible. This may be accomplished by constructing reservoirs with maximum average depth. The point of diminishing returns is reached quickly, however, since the cost of moving soil is great compared to the value of water saved. Assuming the value of water saved to be $0.05 per 1000 gallons, Freeze (5, pp. 47-48) found that an expenditure of $130,000 was justified in eliminating shallow water areas in Lake Worth. This sum was sufficient to pay for 322 acre-feet of fill which eliminated 100 acres of evaporation surface.

Assuming that a reservoir has been constructed with maximum average depth, another source of water loss is evapotranspiration by plants. This loss may be reduced by eliminating, as much as possible, plant life in the water and around the edges of the reservoir.

Underground storage of water may be used to control evaporation losses. Known as "ground water recharging" this method requires taking water from its source and feeding it into an underground reservoir. Here the water is kept until it is needed and pumped to the surface. Legal quarrels, unknown sub-surface losses and limited favorable ground storage formations restrict the extent of this method of reducing evaporation.

Monomolecular surface films have been recommended as evaporation suppressants. Previous testing of these films has been done either on evaporation pans or in reservoirs where seepage was not controlled. Questions have arisen on the validity of conclusions based on this data. Therefore, this study was made to determine the amount of evaporation and evaporation reduction due to the presence of monomolecular films under controlled Oklahoma conditions.

CHAPTER II

OBJECTIVES

The general objective of this study was to determine the effect of certain monomolecular films on the evaporation of water. To accomplish this the following specific studies were made to determine:

1. The pan to reservoir evaporation coefficient.
2. The rate of evaporation from an exposed, untreated water surface.
3. The effect of wind velocity on evaporation reduction due to treatment with a monomolecular film.
4. The effect of wind velocity on monomolecular film area.

CHAPTER III

REVIEW OF THE LITERATURE

Evaporation Equations

The evaporation of water has been the subject of investigation by engineers, meteorologists and physicists. Two basic approaches have been used in the development of various evaporation equations; discontinuous mixing and continuous mixing.

The concept of discontinuous mixing is based on the skin friction of a flat plate as discussed by Prandtl (16). Millar (15, pp. 39-65) developed the most general equation involving the discontinuous mixing concept. His equation is based on the growth of a "vapor blanket" or a "moisture boundary layer" which is analogous to the growth of a momentum boundary layer. As reported by Marciano and Harbeck (14, p. 58) the point evaporation equation integrated to give total evaporation from a circular area with 8 meters as the reference level takes the form

$$V = \frac{0.535\,\rho\, k_o\, u_8\,(e_o - e_i)\, r^{1.865}}{P\,[\ln(800/z_o)]} \qquad (1)$$

Symbols, dimensions, units and descriptions of the terms in the equations are given in Appendix A.

The concept of continuous mixing which was first advanced by Taylor (23) has been applied by Sutton (22) to vapor diffusion. As given by Marciano and Harbeck (14, p. 60) the evaporation from a lake of radius r is

$$V = \frac{0.623\,\rho\,G'}{P}\; u^{\frac{2-n}{2+n}}\; r^{\frac{4+n}{2+n}}\,(e_o - e_i) \tag{2}$$

where

$$G' = \frac{\left(\frac{2+n}{2-n}\right)^{\frac{2-n}{2+n}} \frac{2+n}{2\pi}\, \text{SIN}\left(\frac{2\pi}{2+n}\right) \Gamma\left(\frac{2}{2+n}\right) a^{\frac{2}{2+n}}\; z^{\frac{n^2}{-4-n^2}}\; 2^{\frac{2}{2+n}} \sqrt{\pi}\; \Gamma\left(\frac{3+n}{2+n}\right)}{\Gamma\left(\frac{8+3n}{4+2n}\right)} \tag{3}$$

and

$$a = \frac{(\pi k_o/2)^{1-n}\;(2-n)^{1-n}\; n^{1-n}\; z^{\frac{n^2-n}{2-n}}\;(\tau + u_* z_o)^n}{(1-n)\;(2-2n)^{1-n}} \tag{4}$$

Equations developed from both the discontinuous and continuous mixing concepts require a high degree of instrumentation to evaluate some parameters in the equations. For this reason empirical equations have been developed to predict evaporation under particular meteorlogical conditions. Many of these equations take the form

$$E = C_1\left(1 + C_2 u\right)\left(e_o - e_a\right) \tag{5}$$

This model equation implies that evaporation takes place in the absence of wind.

Marciano and Harbeck (14, p. 61) state that, in the absence of wind, evaporation occurs only by molecular diffusion which is an extremely slow process. Point evaporation in the absence of wind is given by

$$F = \rho D \frac{dq}{dz} \tag{6}$$

which after integration and substitution yields

$$F = \frac{0.623\,\rho D\,(e_o - e_z)}{Pz} \tag{7}$$

Using boundary layer concepts it was pointed out that as u approaches zero, the thickness of the laminar layer approaches infinity. Thus, for z approaching infinity, F in equation (7) approaches zero. It was concluded that in comparison to evaporation under turbulent conditions, evaporation due to molecular diffusion is negligible unless a strong temperature gradient exists.

The empirical equation used to describe evaporation from Lake Hefner is given as

$$E = K\, u\, (e_o - e_a) \qquad (8)$$

which implies no evaporation with zero wind velocity.

Using Yamamoto's (26, p. 354) equation for evaporation into still air and applying Lake Hefner conditions, it was found that the evaporation due to a 5°C temperature difference was equal to that which was found at a wind velocity of 0.32 knot. This gave Marciano and Harbeck (14, p. 61) confidence in dropping the factor correcting for evaporation without wind.

Evaporation Pans

Evaporation pans are used widely to predict evaporation from large bodies of water. An extensive number of comparisons among different types of evaporation pans and water surfaces was made by Rohwer (18). These tests were conducted throughout the United States; however, most of the tests were in the western states. Rohwer (18, p. 687) found that the factor for computing annual reservoir evaporation from pan evaporation using the United States Weather Bureau Class "A" pan was between 0.69 and 0.70. He recommended that this pan be used under representative, standard conditions to predict reservoir evaporation.

From evaporation pan observations in conjunction with the Lake Hefner study Kohler (9, p. 127) noted that the pan to reservoir coefficient varied appreciably. Variations were due to: (1) thermal hold-over due to the larger heat capacity of the lake, (2) obstructions causing a variation in wind movement over the pans, and (3) variations in weather. Kohler (9, p. 146) found an annual pan coefficient for the Class "A" evaporation pan to be 0.69. It was pointed out that the coefficient for a particular month may vary considerably from year to year even though the annual coefficient is stable.

Monomolecular Films For Evaporation Control

It has been known for many years that thin oils are able to calm the actions of stormy seas. It was not until 1917, however, that Langmuir (11) reported that when a sufficient supply of an oil was placed on a confined water surface, it spread until it reached some maximum film pressure.

In 1924 Hedestrand (7) conducted experiments from which he was unable to detect a reduction in evaporation due to the presence of a monomolecular film. However, in 1925 Rideal (17) stated:

> the rate of evaporation of water from a surface is very considerably diminished by the presence of a unimolecular film of fatty acid upon the surface and that this diminution in rate is

> materially affected by the compression or surface concentration of the film.

Work continued until in 1940 Sebba and Briscoe (20) were able to report that the resistance of a film cannot be correlated with its physical state. For instance, the solid film of albumin offers almost no resistance to the passage of water while the liquid film of cetyl alcohol offers great resistance. In addition it was found that the surface pressure of the film greatly biases its effect on evaporation. During the course of their investigation Sebba and Briscoe (21) found that several monomolecular films were soluble in water.

In later trials Sebba and Briscoe (19) found an "ageing effect" which they reported to vary directly with time and inversely with the surface pressure of the film during ageing. They found that a fresh film of n-docosanol with a surface pressure of 47 dynes per centimeter reduced evaporation by 98 per cent; however, after ageing the film for 20 hours at zero pressure and then recompressing it to 47 dynes per centimeter, a reduction of less than 5 per cent was noted. They hypothesized that:

> in an uncompressed film the single molecules, being in active motion and free to associate, gradually do so in pairs, forming double molecules having a hydrophilic alcoholic group at each end, which, being thus akin to the single molecules of dihydroxy-alcohols, lie and remain flat upon the water surface and so greatly enhance the permeability of the film to water.

In testing the hypothesis Sebba and Briscoe found that the area of a given film increased as it aged.

In 1943 Langmuir and Schaefer (10) reported that as little as one part of cholesterol per 1,800 parts of mixed films of C23 reduced the resistance of the acid by about 40 per cent. They concluded that minute amounts of certain foreign materials could have great influence on lowering the film resistance. It was proposed that this contamination effect was responsible for the "ageing effect" reported by Sebba and Briscoe.

Archer and La Mer (1) confirmed the results of Langmuir and Schaefer in reporting that some "small foreign molecules having relatively meagre interactions with the surrounding molecules constitute permanent holes in the film or at least sites of small resistance." The total resistance of the monolayer is the resistance of these sites acting in parallel with sites occupied by the acid molecules. Thus, it was reported, a small concentration of foreign material can greatly decrease the resistance to evaporation.

The theory of monomolecular films was explained by Beadle and Cruse (2) as follows:

> Certain types of organic compounds - fatty acids, fatty amids, fatty alcohols, fatty amines, fatty nitriles, and certain special organic materials - possess the property of forming a film one molecule in thickness when applied to a water surface. These molecules have in their molecular structure a hydrophilic portion which is attracted by water . . . and a hydrophobic portion, attached to one of the . . . hydrophilic radicals, which is repelled by the water.

Thus, when the molecules are standing on end and tightly packed together, a film is formed which resists the evaporation of water. It is reported that the nature of these chemical materials is to spread continuously until confined by some physical barriers so that the spreading pressure of the film is reached.

The first field tests using monomolecular films on open bodies of water were conducted in Australia during 1953. Mansfield (12) reported an average evaporation reduction of 48 per cent using containers 12 inches in diameter and 18 inches deep. In addition a 30 per cent reduction was reported from a reservoir of approximately 2 surface acres. However, the statement on this figure was qualified to the extent that the amount of seepage was unknown. It was further estimated that a treatment of 300 pounds of cetyl alcohol per square mile would have a life expectancy of 10 years.

In 1956 Mansfield (13) published the results of tests on reservoirs ranging in size from pans 3 feet in diameter to lakes with up to 22 surface acres. Evaporation reductions between zero and 90 per cent were reported.

From screening tests conducted on Class "A" evaporation pans by the United States Bureau of Reclamation (25) it was noted that cetyl alcohol gave an evaporation reduction of 64 per cent. Many other materials were tested but none gave as good results as cetyl alcohol.

CHAPTER IV

APPARATUS AND METHOD OF PROCEDURE

Description of Testing Facilities

Two ponds were constructed for the purpose of this experiment. The site for these two ponds was chosen to allow maximum exposure of the water surfaces to meteorlogical elements. A knoll approximately one mile northwest of the Oklahoma State University library in Stillwater, Oklahoma was chosen as a location for the ponds. An adequate water supply was available in the form of the college water supply tower and this location was near enough to the campus to be convenient for making observations. A fence was constructed around the ponds to keep out swimmers and discourage molestation of testing facilities. A general view of the test ponds is given in Figure 1.

The two ponds were constructed as identically as possible with common excavation equipment. The dimensions are 120 feet long by 100 feet wide by 7.5 feet deep as shown in Figure 2. To achieve maximum wind exposure the long dimension was oriented along the north-south axis parallel to predominately southerly summer winds.

Following rough construction a layer of sand was placed over the floor and sides of the ponds to protect the plastic liner which was used as the seepage control. The 8 mil

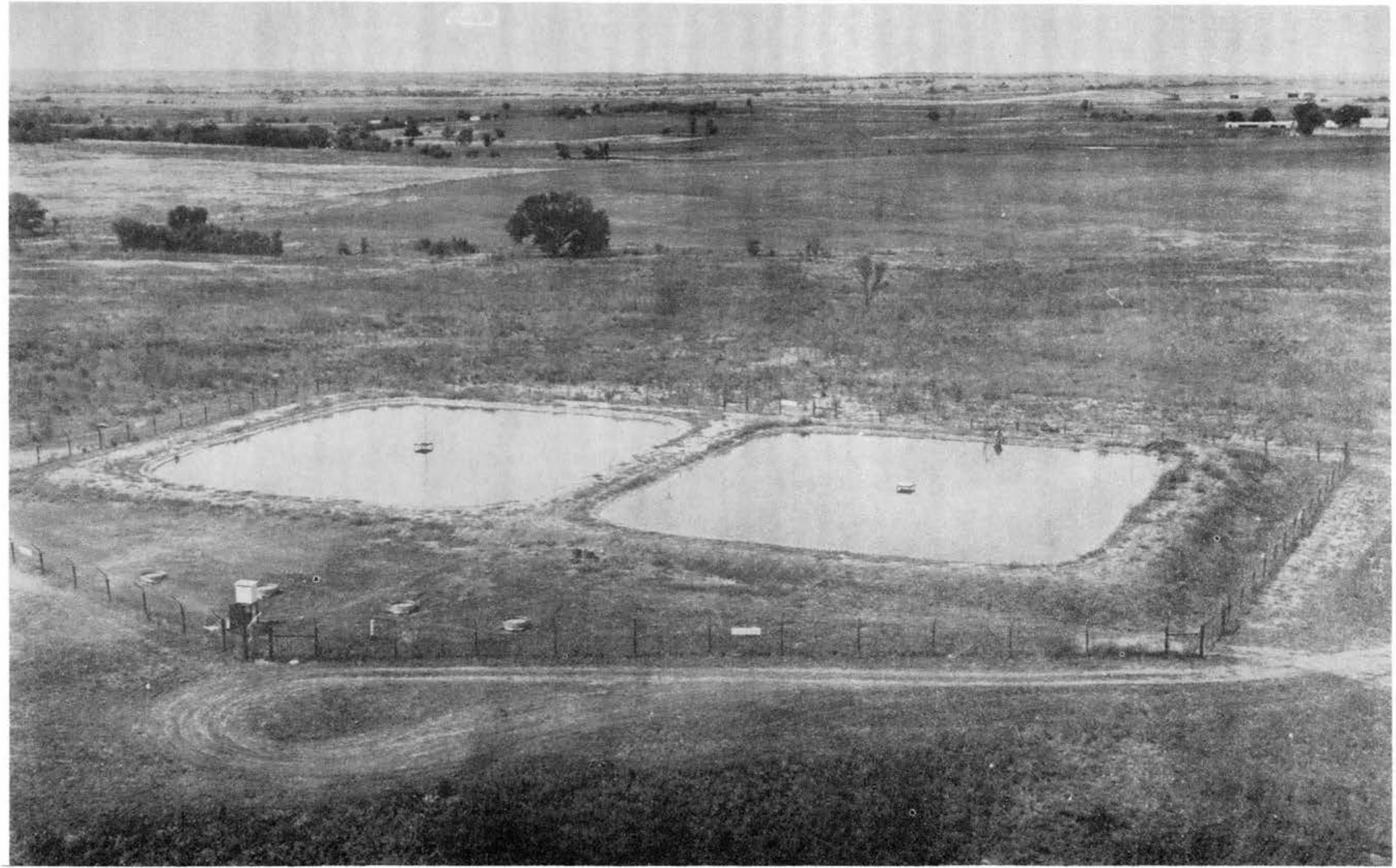


Figure 1. General View of Experimental Ponds

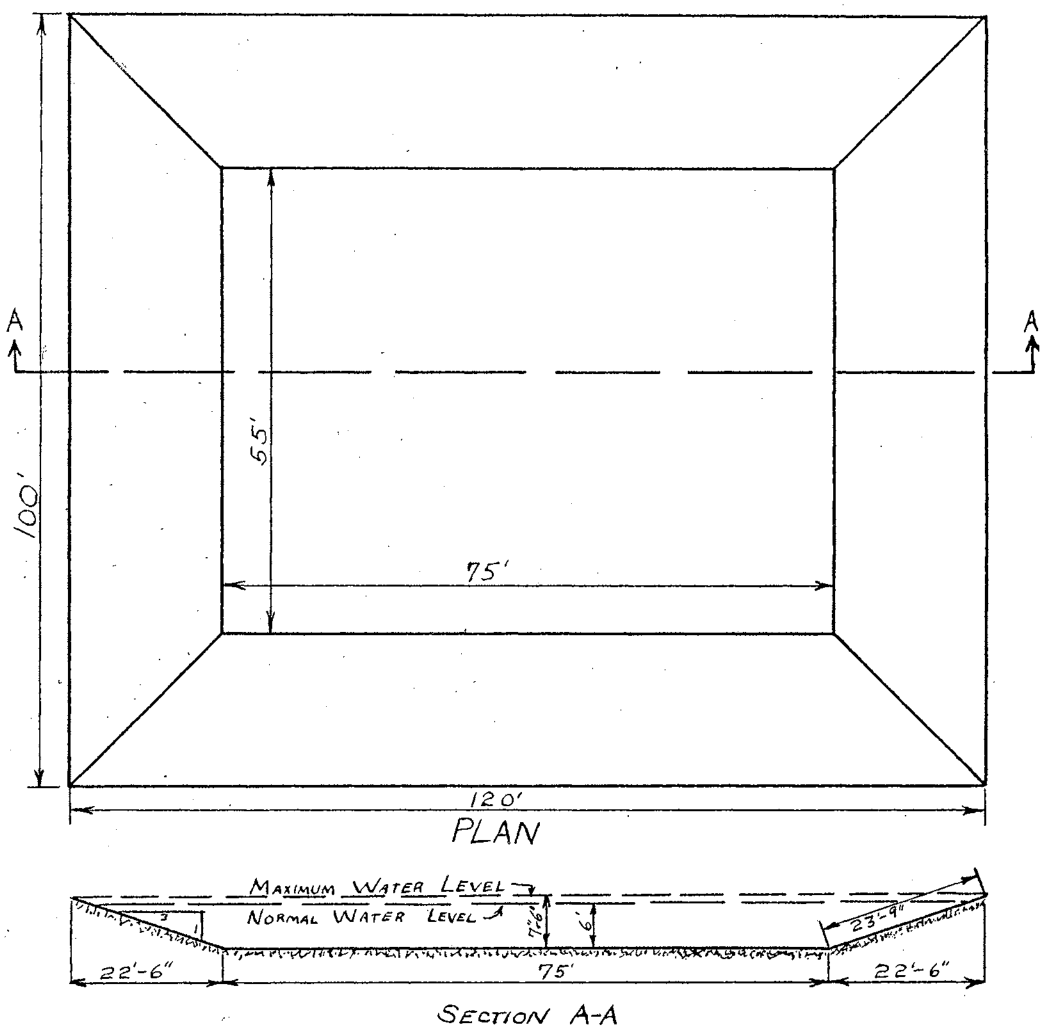


Figure 2. Dimensions of Ponds

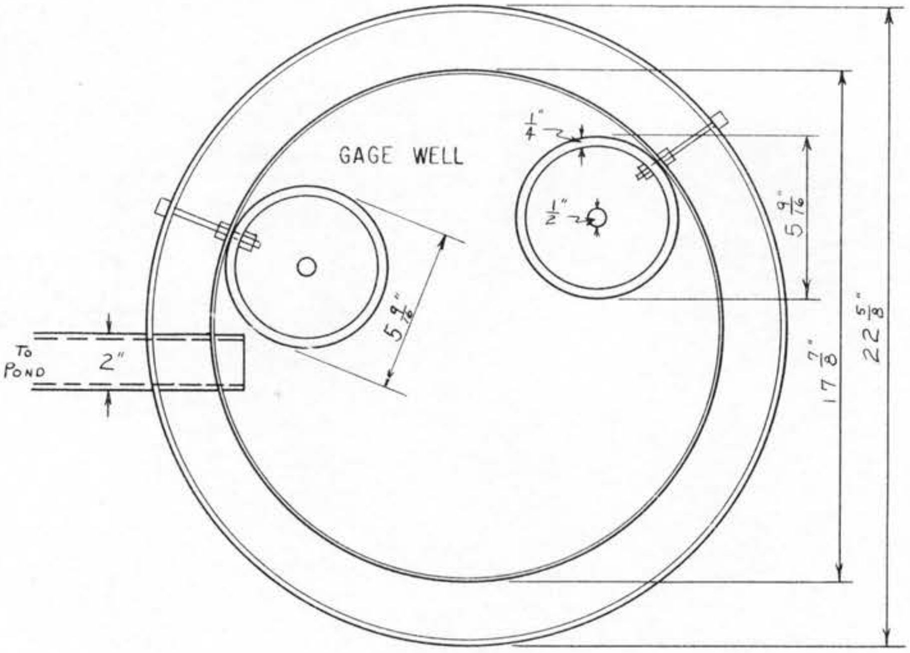
vinyl chloride liner was furnished through the courtesy of the Bakelite Company. Following fabrication the two liners were in complete sections, accordian folded for installation in the ponds. The outside edges were buried in a trench and the liner was backfilled to make it stationary and give it some amount of mechanical protection. An additional strip of liner was placed over the backfill at the surface of the water to control bank seepage and evaporation losses.

Observation Equipment

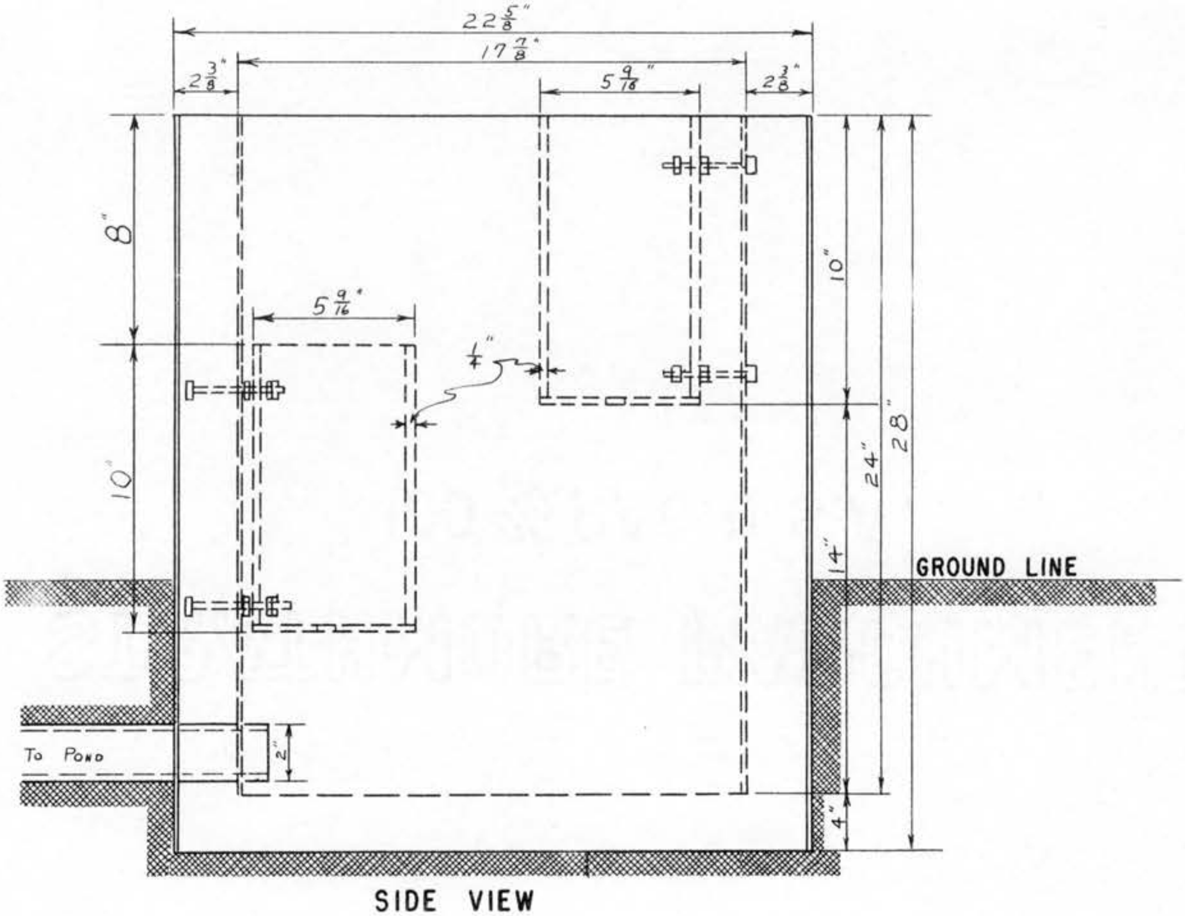
Instruments and equipment used for recording meteorlogic data were: (1) a totalizing anemometer readable to one-tenth mile of wind travel, (2) a Friez hygrothermograph, and (3) a standard 8 inch rain gage. An instrument shelter housed the hygrothermograph.

Stilling wells were constructed to provide means for determining water levels in the ponds. Details are shown in Figure 3. A 2 inch water pipe running to the center of each pond is the inlet to the stilling wells. The center location of the inlet was thought to minimize seiche action caused by wind. The stilling wells are insulated to protect them from freezing during the winter. In each of the two large stilling wells were fastened two small gage wells from which point gage readings were made. The two gage wells were located at heights to bracket the range of water surface levels used during experimentation.

A point gage readable to 0.001 inch was used to observe



PLAN



SIDE VIEW

Figure 3. Details of Stilling Wells

water surface levels. It was equipped with three points of different lengths to extend its range of use.

To compare evaporation with other points in the state a standard Class "A" evaporation pan was used. This pan was circular with a diameter of 4 feet and was 10 inches deep. The pan was supported 2 inches above the ground and the water level was maintained within 2 to 3 inches of the top.

Water surface temperatures were observed by the use of maximum-minimum thermometers which were fastened to strings and floated approximately ½ inch below the water surface of the ponds. The thermometers were graduated at intervals of 2°F and temperatures were estimated to the nearest degree.

Apparatus for Applying Films

One method for applying a film was placing a supply of film source in a floating raft. One type of raft considered to be superior to others used is shown in Figures 4 and 5. This raft is 15 inches square by 3 inches deep. Flotation is supplied through the use of four 4" by 2" by 6" Styrofoam floats located diagonally at the corners of the raft. The floats thus located allowed a maximum unobstructed periphery in contact with the water. Plastic screen mesh was fastened around the periphery to contain the film forming material in the raft. The raft was filled and emptied through a hole in the top.

During tests using ethyl alcohol - film source solutions a staff was designed to hold the solution feeder over the

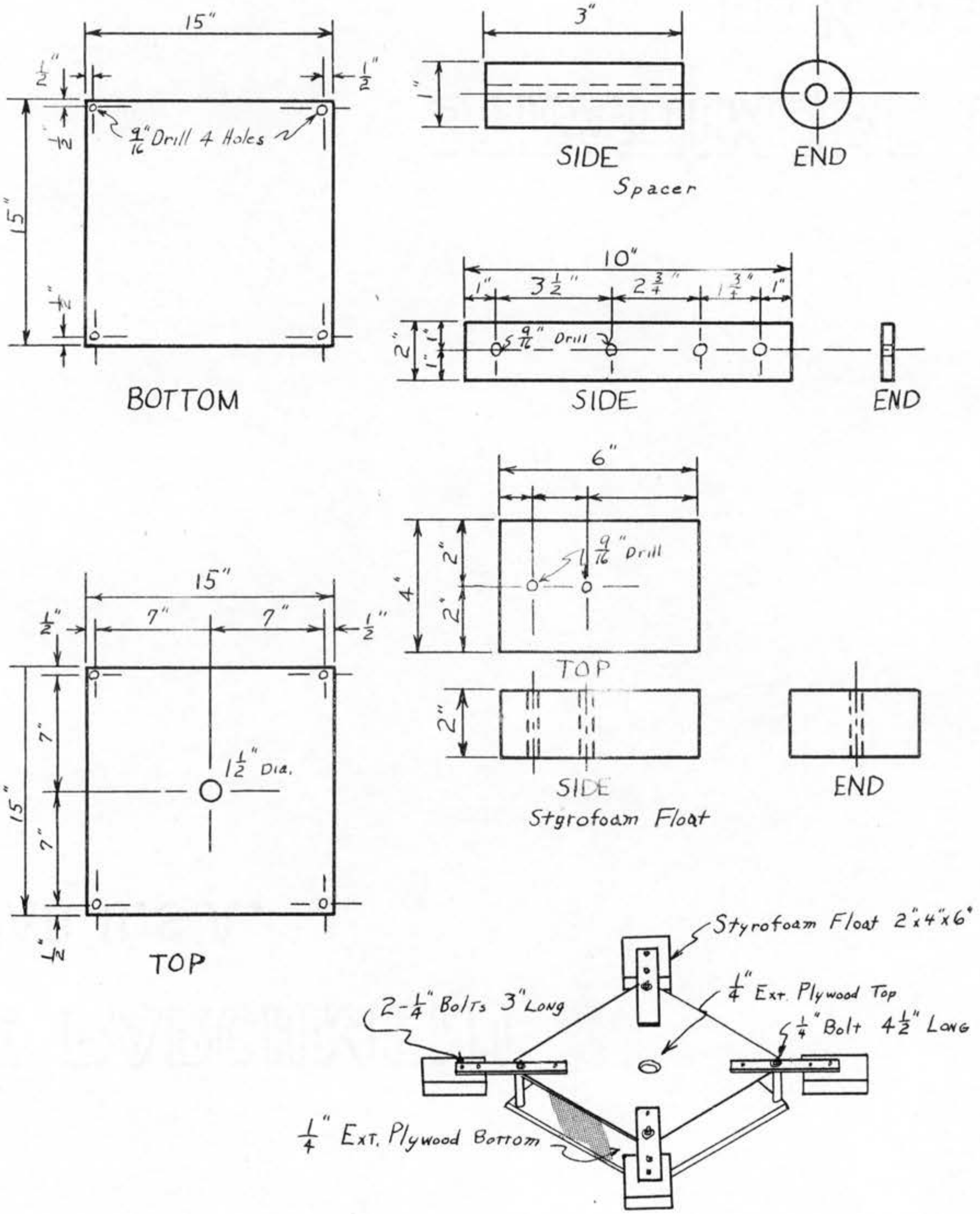


Figure 4. Details of Film Dispensing Raft

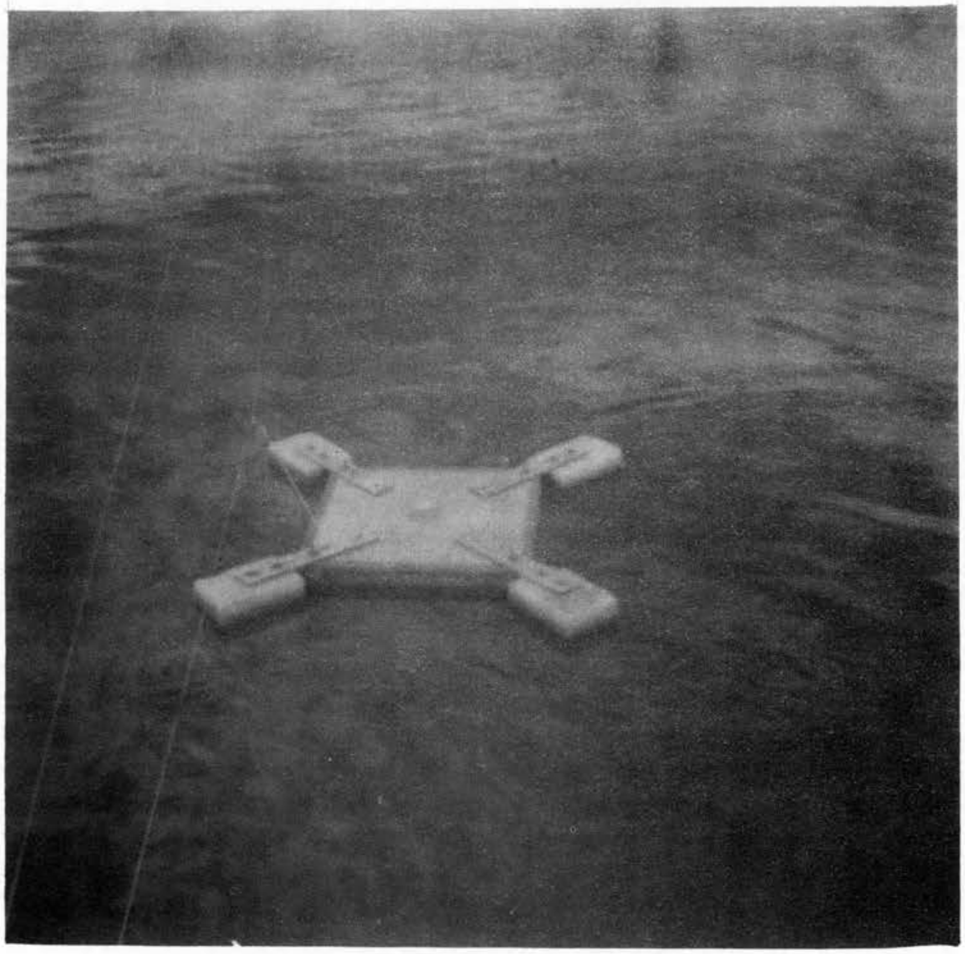


Figure 5. Photograph of Raft

water surface and in addition allow for easy refilling of the feeder. Figures 6 and 7 give details of the staff and solution feeder. Stations were constructed in the center of the north, west, and south dikes of the East Pond for use with the feeder staff. Each station consisted of an 18 inch piece of capped $1\frac{1}{2}$ inch pipe driven into the ground. The $1\frac{1}{4}$ inch solution feeder staff fitted into the station holder and was locked into position by a set screw.

Procedure for Gathering Data

Daily observations were made at the ponds as near 8:00 A.M. as possible. After noting the date, hour and observer, the rainfall for the past 24 hour period was measured in the rain gage to the nearest 0.01 inch. Following this the maximum and minimum temperatures and relative humidities and their respective times during the previous 24 hours were noted. To determine average wind velocity during the observation interval an anemometer reading was taken before and after the pond water level readings. Maximum, minimum and current water surface temperatures for the previous 24 hours were then recorded.

Observations of pond water levels were made with the point gage after the gage well, point length and time were noted. Since the gage wells were constructed of steel, they had a tendency to corrode and needed to be cleaned before point gage readings were made. Following a thorough wetting of the point it was raised out of the water and then lowered

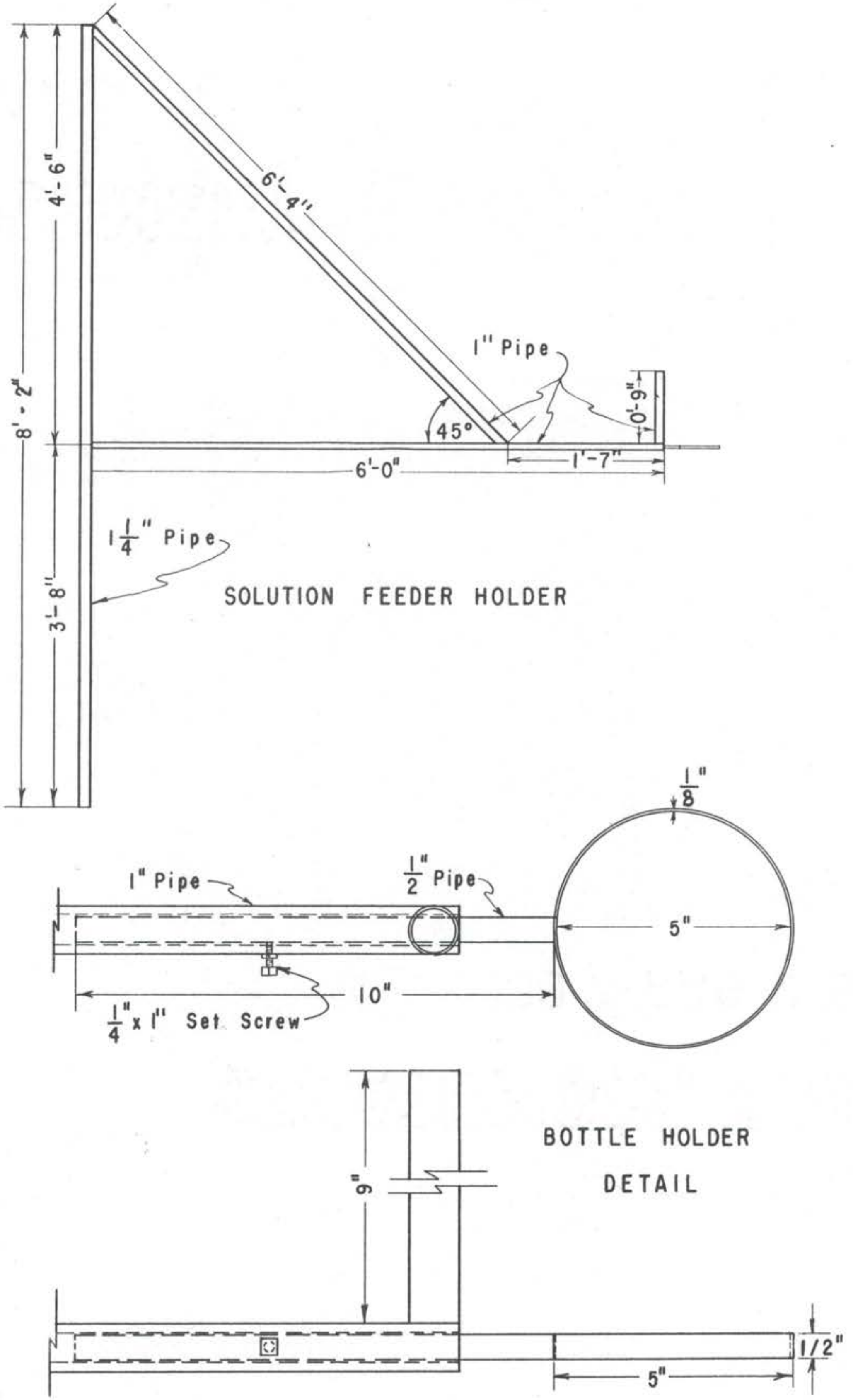


Figure 6. Drawing of Solution Feeder Staff

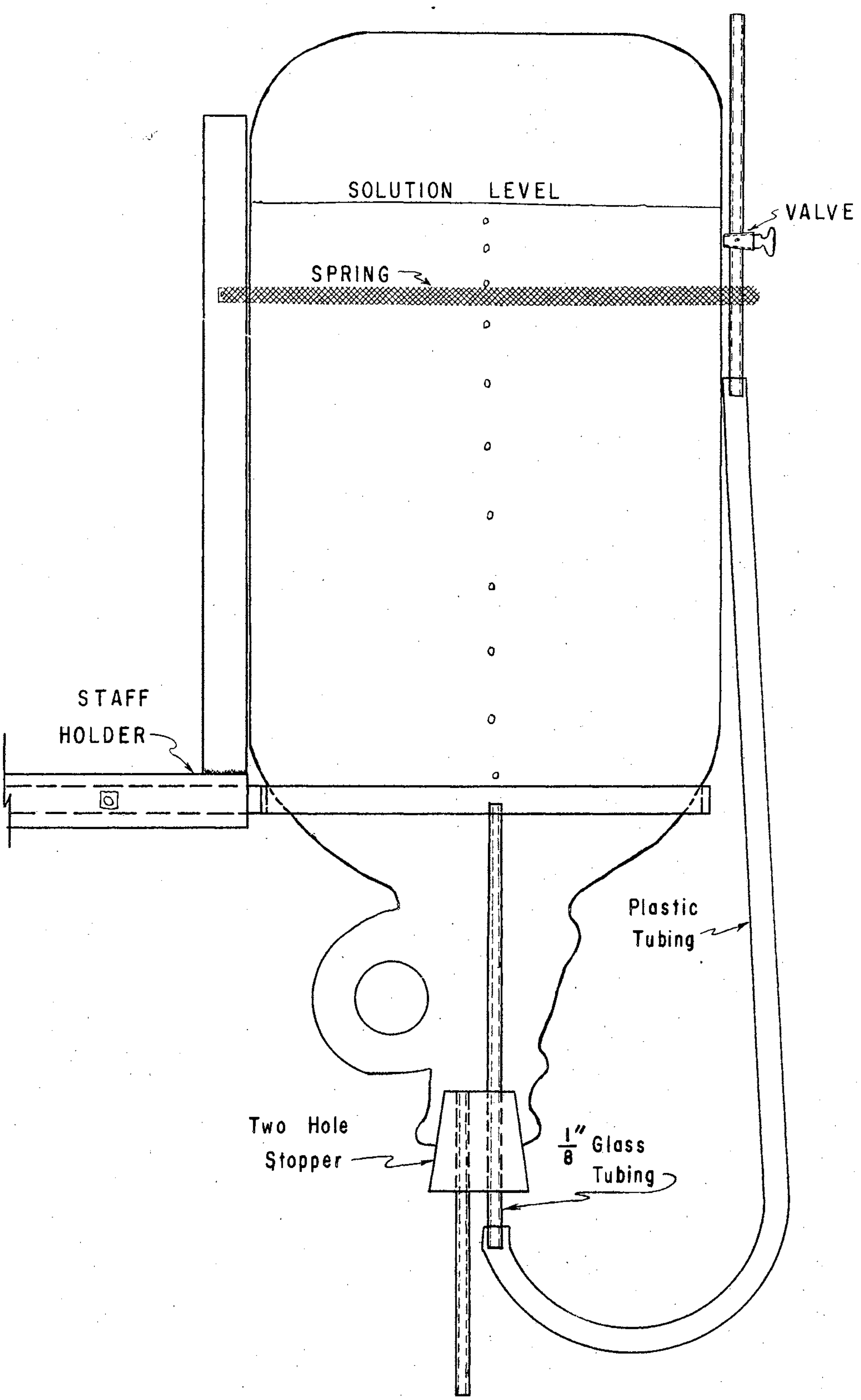


Figure 7. Drawing of Solution Feeder

until the water surface and gage point were observed to meet. The point gage scale reading was then noted. From 10 to 50 readings were taken in each stilling well per observation depending upon wind velocity and seiche action. The average time required to record 50 readings was 7 minutes.

Following the pond level observations the point gage was used to read the water level in the evaporation pan. Only 10 readings were taken in the pan since seiche action was not so prevalent in the small volume of the pan.

Appendix B is a sample data sheet.

CHAPTER V

ANALYSIS OF DATA

Pan to Pond Evaporation Coefficient

Data were taken from a Class "A" evaporation pan and the West Pond which had an untreated water surface over a period of 12 months beginning on April 1, 1957 and ending March 31, 1958. Pond evaporation was divided by pan evaporation to determine the pan to pond evaporation coefficient. Table I gives the monthly summaries.

TABLE I

PAN TO POND EVAPORATION COEFFICIENTS

Month	Number of Observations	Evaporation (in.) Pond	Evaporation (in.) Pan	Monthly Coefficient
April 1957	7	1.196	1.961	0.610
May	16	3.001	3.991	0.752
June	12	2.738	3.831	0.715
July	23	6.754	8.761	0.771
August	22	5.738	7.876	0.729
September	17	3.183	4.364	0.729
October	11	1.470	2.099	0.700
November	12	0.931	1.189	0.783
December	8	0.968	1.312	0.738
January 1958				
February	2	0.247	0.413	0.598
March	7	0.659	1.021	0.645
Total	137	26.885	36.818	0.730

Since observations were made on a total of 137 days, the resulting data must be treated as part year data which according to Kohler (9) is likely to be erratic. Monthly coefficients varied from 0.598 to 0.783 which gave an average coefficient of 0.730. This observed coefficient is greater than 0.70 which is used throughout the United States.

With data from one month missing and sparse data from other months the fact that the observed coefficient is fairly close to the universal coefficient would lend confidence in using the universal annual coefficient of 0.70 for estimating evaporation from large bodies of water.

Pond Evaporation Equation

Observations on evaporation from the West Pond were made from March 21, 1957 to March 31, 1958 and were analyzed to determine an equation which would predict evaporation under given conditions. These data may be found in Appendix C. All days which yielded biased data were excluded, that is, days during which rainfall occurred, 2 or 3 day average observations, and days during which ice covered the water surface. This left a total of 137 daily observations which were analyzed.

The model used for writing the equation is in the form $E = C_1 (1 + C_2 u)(e_o - e_a)$ where C_1 and C_2 are experimental constants, u is a 24 hour average wind velocity and $(e_o - e_a)$ is the average vapor pressure difference in pounds per square inch between the water surface and the atmosphere. Using observed data and fitting the model by least squares using the abbreviated Doolittle procedure the equation takes the values $E = 0.75\ (1 + 0.017u)(e_o - e_a)$ where E has the units inches per 24 hours, u is average wind velocity in miles per hour per 24 hours, and $(e_o - e_a)$ is average vapor pressure difference between the water surface and the atmosphere in pounds per square inch per 24 hours. Ninety-five per cent confidence intervals on the experimental constants gave the following values.

$$0.718 \leq C_1 \leq 0.783$$
$$0.016 \leq C_2 \leq 0.018$$

The "t" test on both constants was highly significant. That is, it is highly improbable that either one of the constants could equal zero.

The "F" test was made on both variables in the equation, $u(e_o - e_a)$ and $(e_o - e_a)$. In both cases the computed "F" value was highly significant which gave confidence in the choice of variables. The analysis of variance is given in Table II.

TABLE II

ANALYSIS OF VARIANCE OF WEST POND EVAPORATION

Source	Degrees of Freedom	Sum of Squares	Mean Square
Total	137	5.974820	
Regression due to $(e_o - e_a)$	1	5.345303	5.345303
Regression due to $u(e_o - e_a)$	1	0.132496	0.132496
Error	135	0.497021	0.003682

A second model was used which is identical to the one used in the Lake Hefner study having the form $E = Ku(e_o - e_a)$. This model implies that no evaporation takes place in the absence of wind. The Lake Hefner equation corrected to

English units is $E = 0.153\ u\ (e_o - e_a)$ where u is in miles per hour per 24 hours and $(e_o - e_a)$ is in pounds per square inch per 24 hours. The same model applied to data from this experiment gave $E = 0.176\ u\ (e_o - e_a)$. The "t" value in testing $K = 0$ was highly significant and the 95 per cent interval estimate gave the range $0.1568 \leq K \leq 0.1958$. From this information the conclusion was drawn that K was not equal to zero.

It is apparent that the two above equations differ only in the experimental constant. Also, the Lake Hefner constant, 0.153, very nearly falls within the confidence interval set on the experimental constant from this experiment. A difference does exist, however, for which some explanation may be found.

A seepage correction was made on Lake Hefner data whereas seepage was assumed to be zero in this experiment. If some seepage did occur through the plastic liner, it would tend to increase the experimental constant. In addition, wind velocities were measured at a height of 8 meters and at a point 13 miles from Lake Hefner while wind velocities during this experiment were measured at a height of 2 meters. The greater height would tend to lower the experimental constant. Admittedly, instrumentation at Lake Hefner was of better quality than that used in this experiment. After considering these differences and the direction of their bias, it may be concluded that the two equations describe evaporation under their respective conditions with sufficient accuracy.

Precision of Experiments

Four calibration checks were made comparing the two test ponds in an untreated condition. These checks were made to determine whether the two ponds were reacting similiarly to identical conditions. Results are shown in Table III.

TABLE III

RESULTS OF CALIBRATION CHECKS

Test Number	Dates	Cumulative Evaporation West Pond	East Pond	Per Cent Variation
4	June 24-July 8, 1957	2.855	2.843	-0.422
6	July 22-Aug. 3, 1957	2.939	3.068	4.205
11A	Nov. 13-Nov.22, 1957	0.613	0.597	-2.680
13	Dec.14,1957 - March 31, 1958	3.956	3.879	-1.985

From this data it may be concluded that inherent oscillatory differences existed between the two ponds which for periods of two weeks or more amounted to as much as 5 per cent. Turbidity in the ponds was noted to vary. This was readily visible since at one time the water in one pond was very murky in comparison to the other. Both ponds had this tendency but at different intervals.

A definite rise and fall in point gage readings during the observation intervals was noted. The magnitude of this swell or seiche action was dependent upon wind velocity. Figure 8 is a plot of 150 point gage readings during an observation interval giving a general idea of the variations encountered during high wind velocities. If only 10 readings

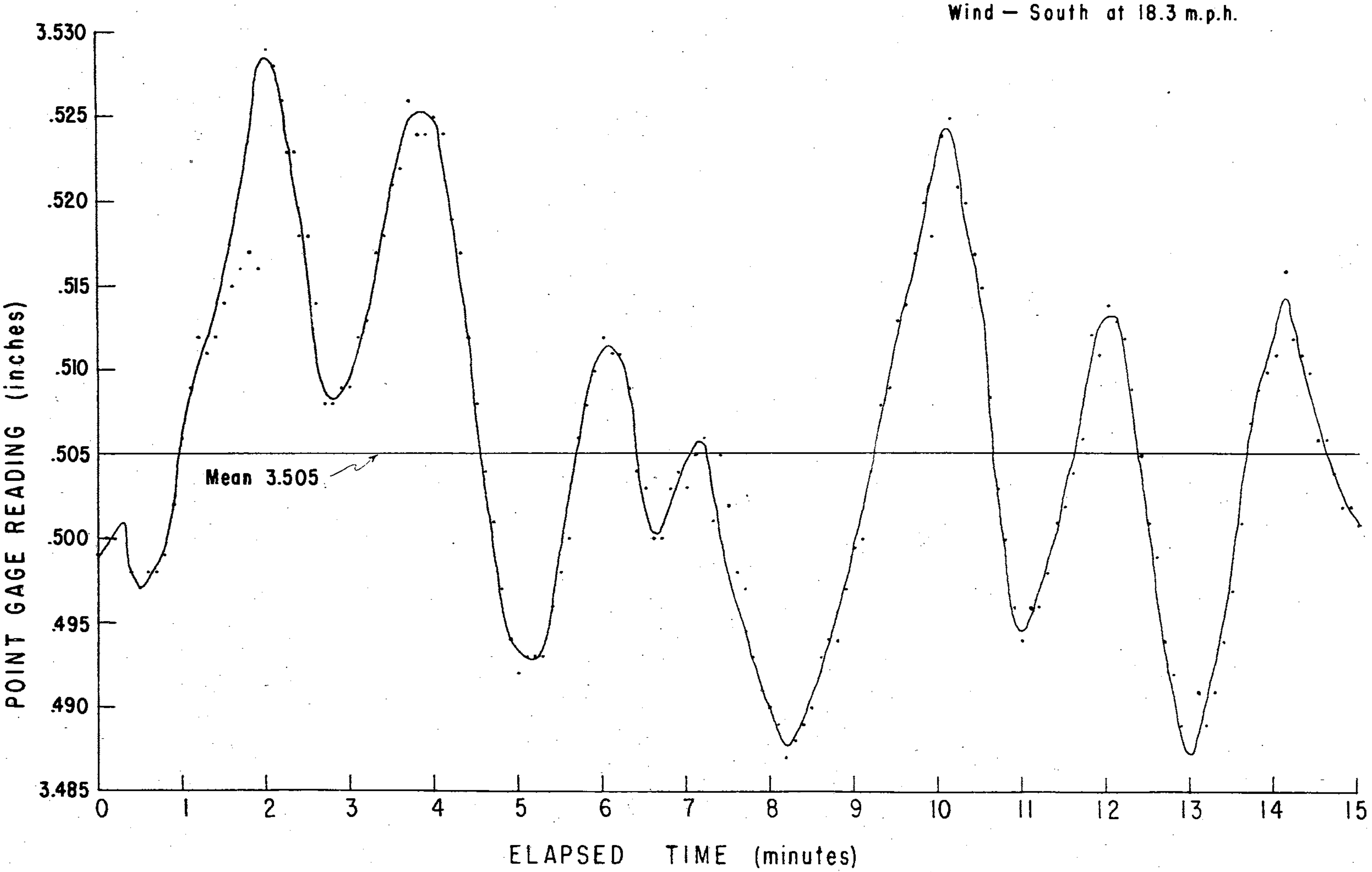


Figure 8. Variation of Point Gage Readings

were taken during an observation and the daily evaporation was small, it was possible to have an error in daily readings in excess of 100 per cent. Over a period of time, however, these errors were compensating and any error left in the test was the error in the first and last readings. This error was estimated to be less than 2 per cent for a test period of 10 days.

The estimated precision of a test is plus or minus 7 per cent. While this is a rather large interval, it is sufficiently sensitive to evaluate the amount of evaporation reductions expected in this experiment.

Evaporation Reduction With Monomolecular Films

Raft Tests

The first tests on evaporation suppression by monomolecular films in this experiment were conducted using rafts containing a film source. The first rafts were furnished by the Southwest Research Institute. These were followed by two types of rafts designed at the Oklahoma State University. The raft described earlier was finally chosen as being best of those tried.

Two physical types of film sources were used, flakes and pellets. Both Adol 52 (a hexadecanol mixture) and Adol 62 (an octadecanol mixture) were used. It was observed that the flakes were quickly dispersed through the screen wire mesh of the raft due to the brittle consistency of the flakes and abrasion caused by wave action. Pellets were found to last longer than flakes and were used for the remainder of the raft tests. Table IV gives results obtained from raft tests.

TABLE IV

RESULTS OF RAFT TESTS

Test Number	Dates	Film Source	Evaporation (in) West Pond	East Pond	Per Cent Reduction
1	May 1-15, 1957	10# Adol 62 Flakes 4 rafts	1.466	1.392	5.32
2	May 22-31, 1957	8# Adol 62 Pellets 8 rafts	1.119	1.069	4.68
3	June 6-21, 1957	16# Adol 62 Pellets 16 rafts	2.857	2.759	3.55
5	July 8-18, 1957	8# Adol 52 Pellets 8 rafts	2.671	2.711	-1.48
7	Aug. 5-20, 1957	0.5# Powder 2# Adol 62 Pellets Fresh Every 4 Days	2.801	2.772	1.05

In none of the raft experiments did the observed evaporation reduction exceed the limits of experimental precision. Therefore, it cannot be stated that an evaporation reduction was observed.

Several explanations may be offered for these results. It was noted that the film source, both pellets and flakes, became discolored after being in the water for several days. This discoloration may have been due to bacteria or colloidal suspensions in the water. In either case a source thus covered failed to produce a film in a pan of clean water. Thus, it must be concluded that the film source became in-active after being coated in this manner. In addition to the coating on the film source a moss like growth was noted on the screen mesh of the raft which impeded the spreading action of the film.

Following these observations raft tests were discontinued in a effort to find some more suitable means of generating a film.

Solution Tests

Both octadecanol and hexadecanol are soluble in ethyl alcohol which was available for use in this experiment. One pound of either film source was put in solution with 2400 milliliters of ethyl alcohol and this solution was applied to the East Pond. Table V gives the results of these film applications.

TABLE V

RESULTS OF SOLUTION TESTS

Test Number	Date	Film Source	Evaporation(in.) West Pond	Evaporation(in.) East Pond	Per Cent Reduction
8	Aug. 23-Sept.10 1957	3/4# Adol 62 in solution per day	4.529	4.166	8.71
9	Sept. 16-25, 1957	1/2# Adol 52 in solution per day	1.369	1.302	5.15

These results are somewhat better than those observed with the use of rafts. A milky curd was formed during heavier applications which may have been responsible in part for the increase in evaporation reduction. This curd was found on the downwind side of the pond during the entire test and sometimes covered as much as 1/4 of the pond surface.

During wind velocities in excess of 5 miles per hour a strip of film 4 to 6 feet wide was observed to stretch across the pond beginning at the applicator. Figures 9 and 10 are photographs of this strip. As the strip of film approached the downwind dike it spread across the width of the pond. This phenomena created an interest in the author to further study the effects of wind on the monomolecular film.

Considerable difficulty was found in applying the solution film source. The solution tended to precipitate as it cooled and clogged the drip applicator. After unsuccessful attempts to perfect this applicator, emphasis was shifted toward applying the films in the powdered form.

Powder Tests

Powdered Adol 62 and Adol 52 were sprinkled directly on the East Pond from the upwind dike. Upon application a film was observed to spread rapidly in the immediate vicinity of application. The film then moved across the pond with the wind and became stationary against the downwind dike. Results of powder tests are given in Table VI.

In an effort to slow the movement of the film across the pond a barrier of Styrofoam floats was made and placed across the upwind portion of the pond. The film was then applied behind the barrier. Some slowing of the film was observed but the entire slick still moved across the pond

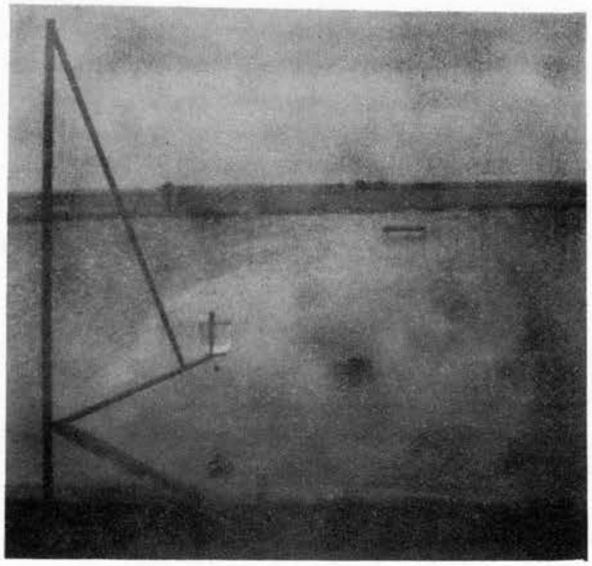


Figure 9. The Solution Feeder and Film Strip

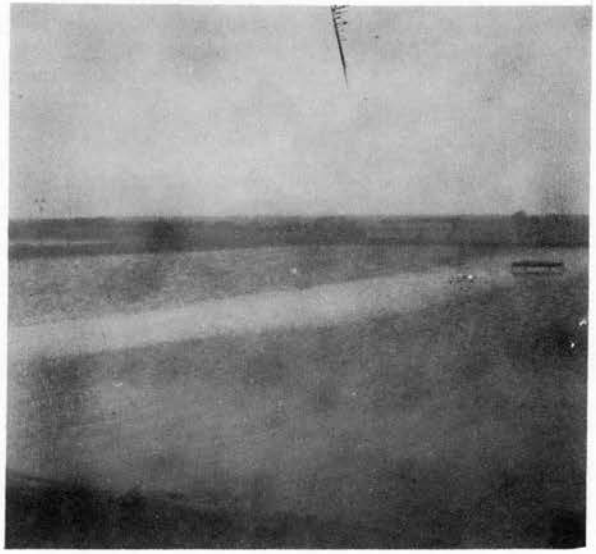


Figure 10. A Solution Film Strip

in about 15 minutes.

TABLE VI

RESULTS OF POWDER TESTS

Test Number	Date	Film Source	Evaporation(in.) West Pond	Evaporation(in.) East Pond	Per Cent Reduction
10	Sept.30-Oct.12 1957	½# Adol 62 powder/day	1.347	1.206	11.69
11	Oct.19-Nov.11 1957	½# Adol 62 powder/day behind barrier	1.634	1.483	10.18
12	Nov.12-Dec.9 1957	½# Adol 52 powder/day behind barrier	1.396	1.322	5.60

Significant evaporation reductions were noted through the use of Adol 62 powder sprinkled directly.

Wind Effect on Evaporation Reduction

The empirical equation predicts that evaporation increases with wind velocity. This implies that, if an evaporation retardant maintains the same degree of effectiveness, the per cent evaporation reduction will increase with wind velocity. A study was made of the evaporation reduction tests to determine if this relation was true.

Since the tests had different treatments, they were each analyzed separately. The analysis was made by comparing a 24 hour average wind velocity with the same 24 hour evaporation reduction. Following comparisons of plots on semi-log, log-log and rectangular coordinate paper the data were concluded to plot as a straight line on rectangular coordinate graph paper. A least squares curve was then fitted to the data.

A typical curve relating wind velocity and evaporation reduction for the raft tests is given in Figure 11. The equation $R = 8.48 - 0.521u$ indicates that evaporation reduction increases to a maximum as wind velocity approaches zero. Conversely, evaporation reduction approaches zero as wind velocity increases.

The extreme variation between plotted points may be attributed to errors in daily pond water level readings. The small correlation coefficient, -0.1987, for test number 3 reflects these fluctuations and allows little confidence in the slope of the regression curve.

Figure 12 is a curve typical of those plotted from tests using solution as a film source. The relation was found to be $R = 20.39 - 1.937u$ with a correlation coefficient of -0.498 which allows moderate confidence in the slope of the curve.

The relation shown in Figure 13 is typical of those found when using powder as a film source. This equation has the values $R = 47.52 - 6.663u$ with a correlation coefficient of -0.905 which allows relatively good confidence in the slope of the curve.

The correlation coefficients may be noted as increasing with the number of tests. Two reasons for this are: (1) the amount of daily evaporation increased which lessened the effects of errors in making readings, and (2) the number of readings taken at one observation were increased which tended

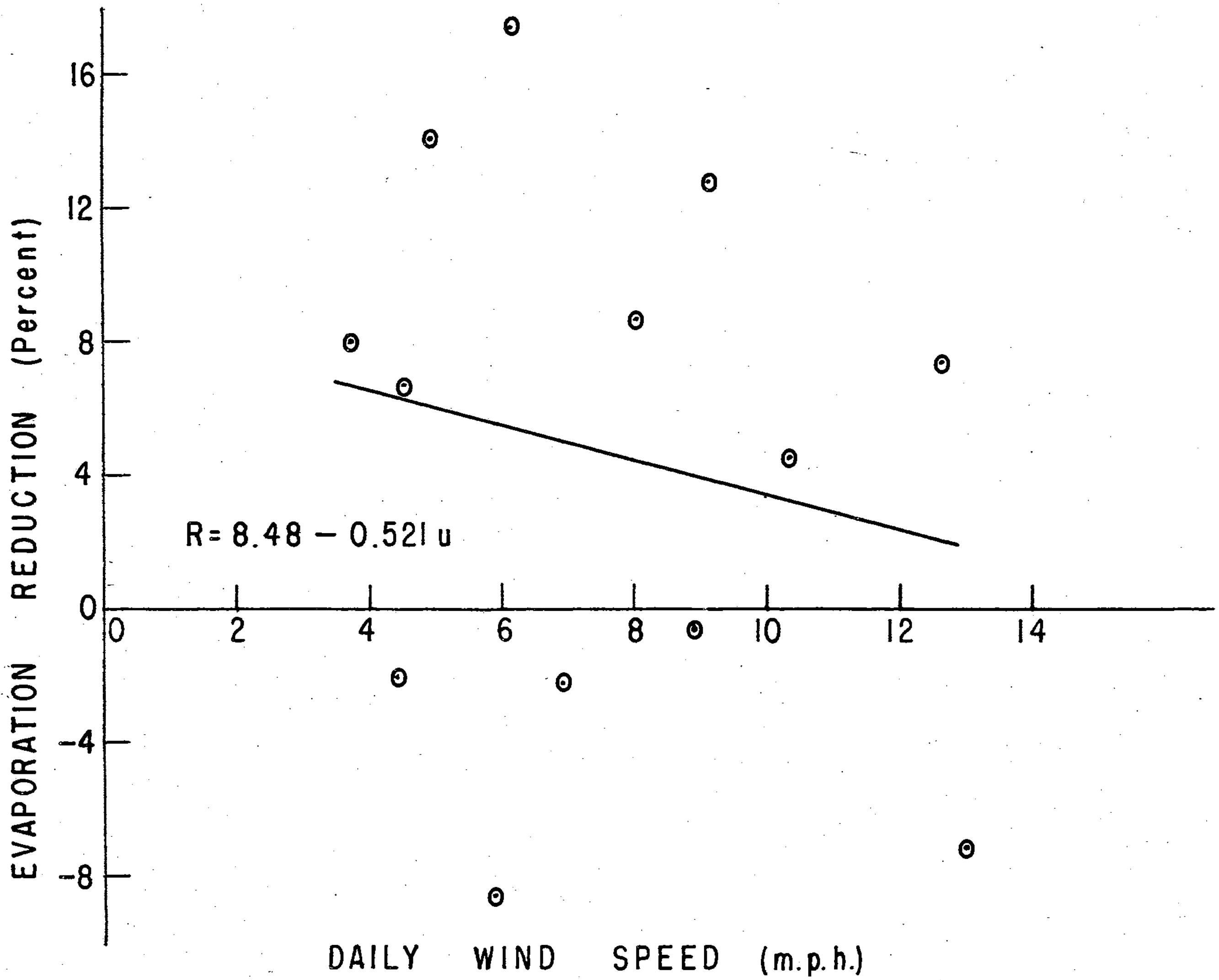


Figure 11. Effect of Wind Speed on Evaporation Reduction - Test Number 3

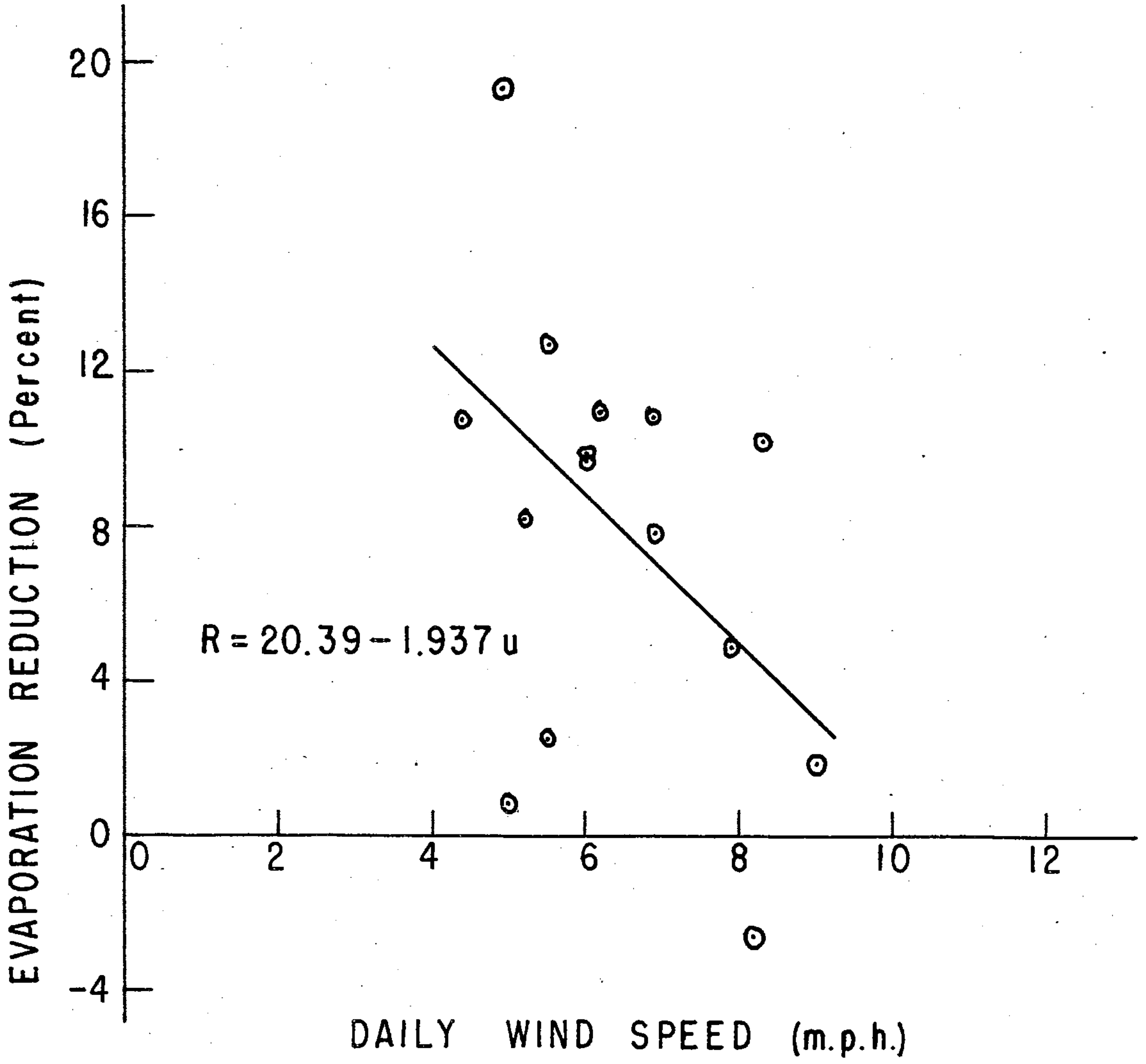


Figure 12. Effect of Wind Speed on Evaporation Reduction - Test Number 8

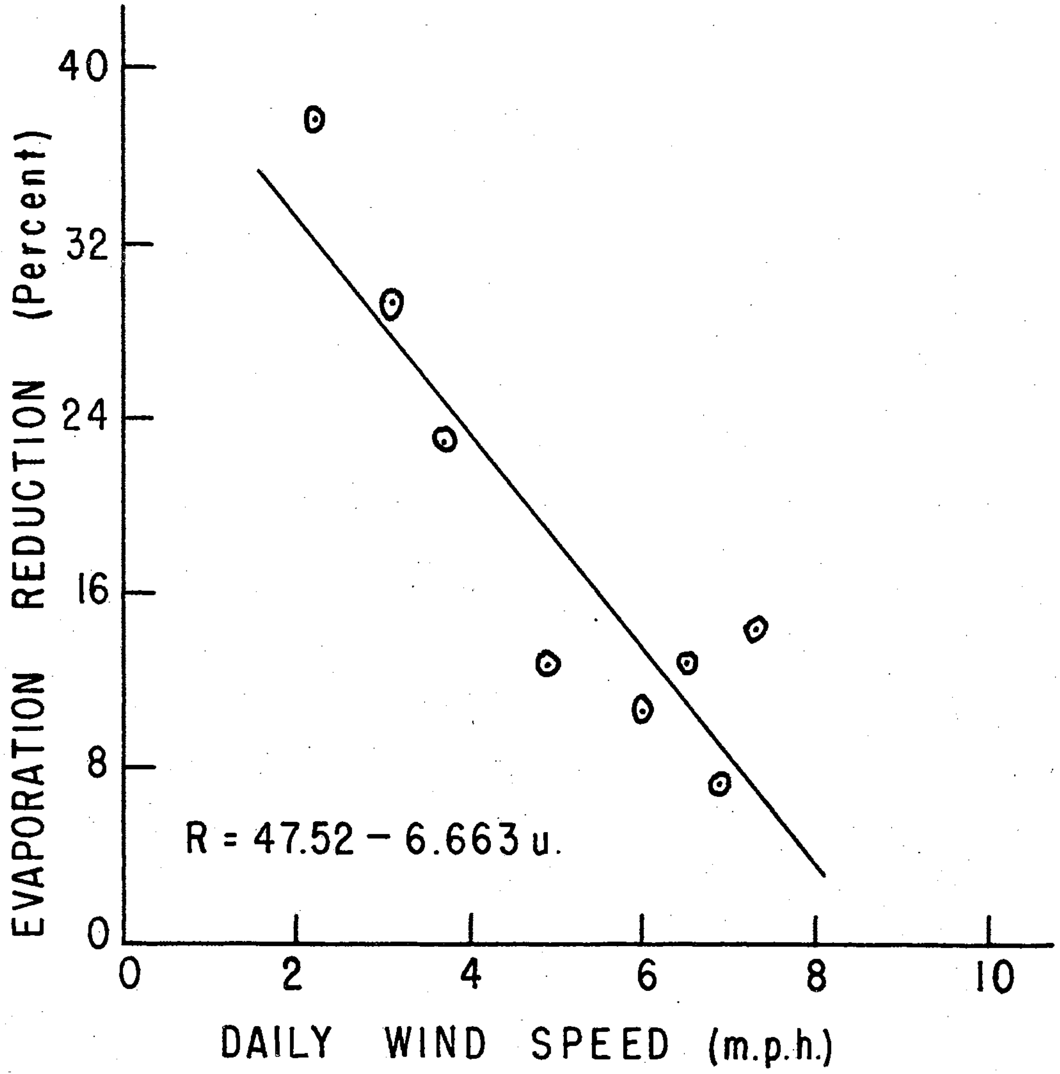


Figure 13. Effect of Wind Speed on Evaporation Reduction - Test Number 10

to lessen daily errors. Relationships of all tests, their correlation coefficients and range of wind velocities may be found in Appendix D.

A definite trend may be noted from an observation of these curves, that is, evaporation reduction decreases as wind velocity increases. It may be hypothesized, then, that wind velocity hinders the effectiveness of a monomolecular film in suppressing water evaporation.

Wind Effects on Film Area

The successful determination of wind and film distribution relationships was dependent upon some practical method of detecting the film and its spreading pressure. The Bureau of Reclamation (24) has reported a satisfactory method of measuring film pressures with the use of indicator oils. These oils are a mixture in various proportions of dodecyl alcohol and mineral oil and are calibrated to have spreading pressures from 5 to 42.5 dynes per centimeter. The pressure of a monolayer on the water surface was determined by placing a drop of the indicator oil on the surface. If the drop spread, it had a higher spreading pressure than the monolayer. If the indicator oil did not spread, but formed a lens, the monolayer film pressure was greater than that of the indicator oil. Thus, the presence and spreading pressure of a monolayer was determined by bracketing the film pressure of the monolayer.

Using the above described method, a number of observations of film area and pressure distribution for varying wind velocities were made during test 8. A typical film-area pressure pattern is shown in Figure 14. The per cent of pond area covered by films of 15, 30, and 42.5 dynes per centimeter was determined and found to approach a straight line on log-log graph paper when plotted as a function of wind velocity. A least squares fit was then developed for each of the film pressures as shown in Figure 15. This plotting shows that film area increases as wind velocity decreases. Extrapolation beyond the range of data indicates that a 42.5 dynes per centimeter film may cover 100 per cent of the water surface only during very low wind velocities. For wind velocities in excess of 10 miles per hour no film was apparent.

The relations shown in figures 12 and 15 have one variable in common, wind velocity. Therefore, these two curves may be used to derive a possible relation between film coverage of 42.5 dynes per centimeter and evaporation reduction. This relation is shown in Figure 16.

Figure 16 was derived from data resulting from wind speeds of 4 to 9 miles per hour and should not be extrapolated beyond the range of test data. Also, the per cent film area- evaporation reduction relations vary with the geometry of the reservoir which limits the applicability of the data.

The curvilinear relation of Figure 16 is due to the plotting of the common variable, wind velocity. In Figure 12

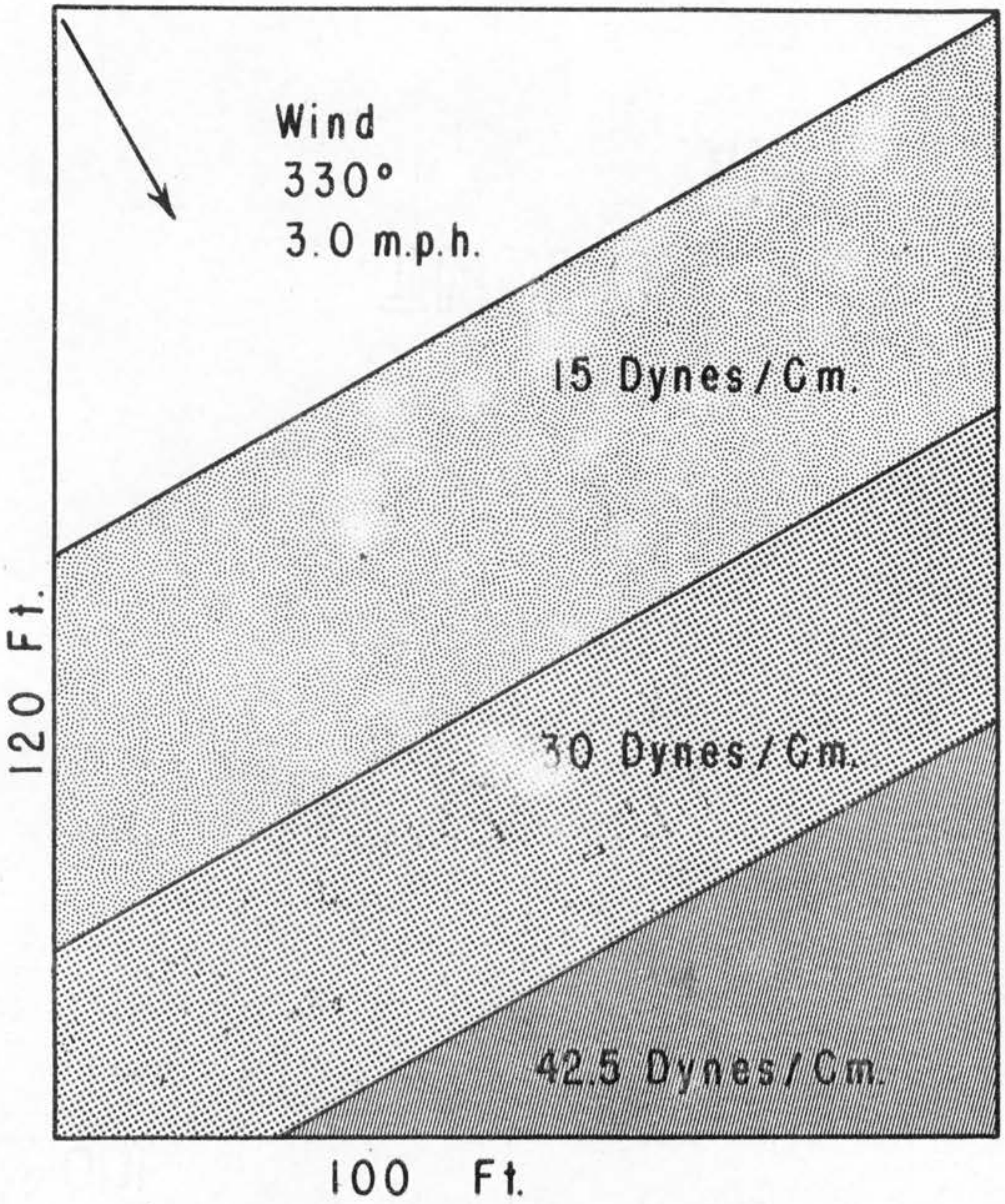


Figure 14. Film Area Pressure Distribution

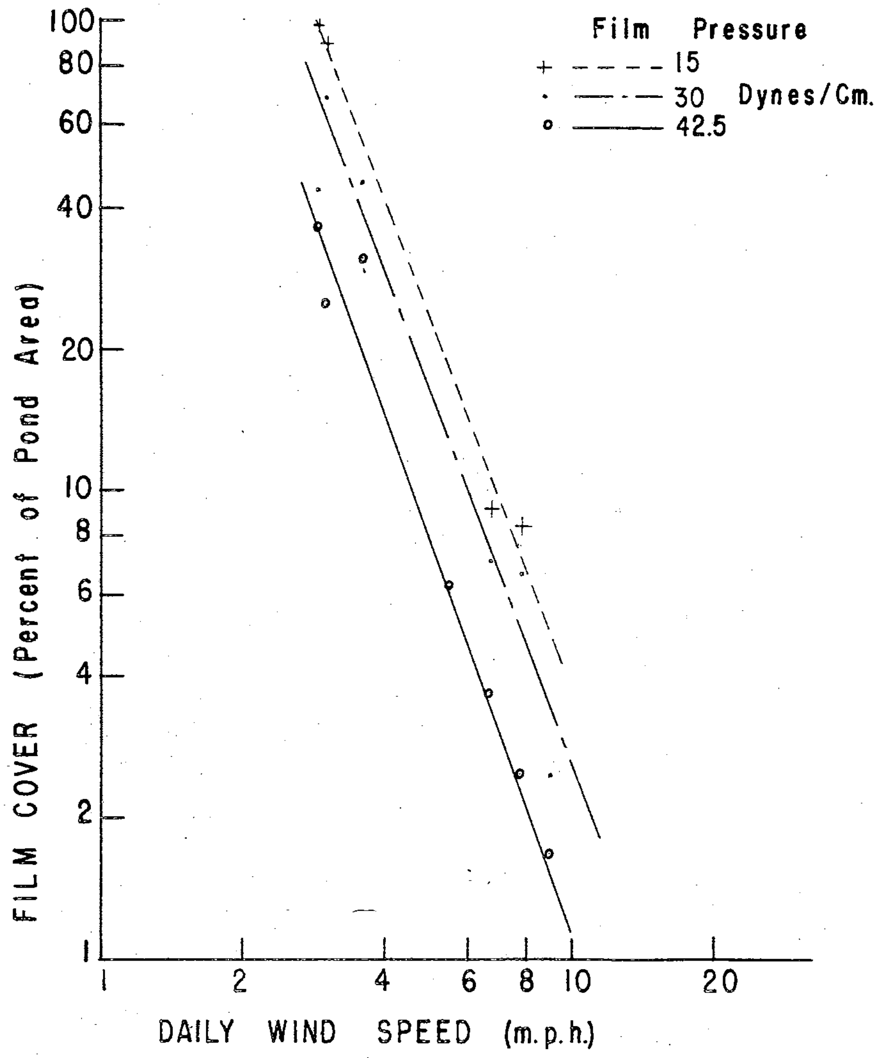


Figure 15. Effect of Wind Speed on Film Area - Test Number 8

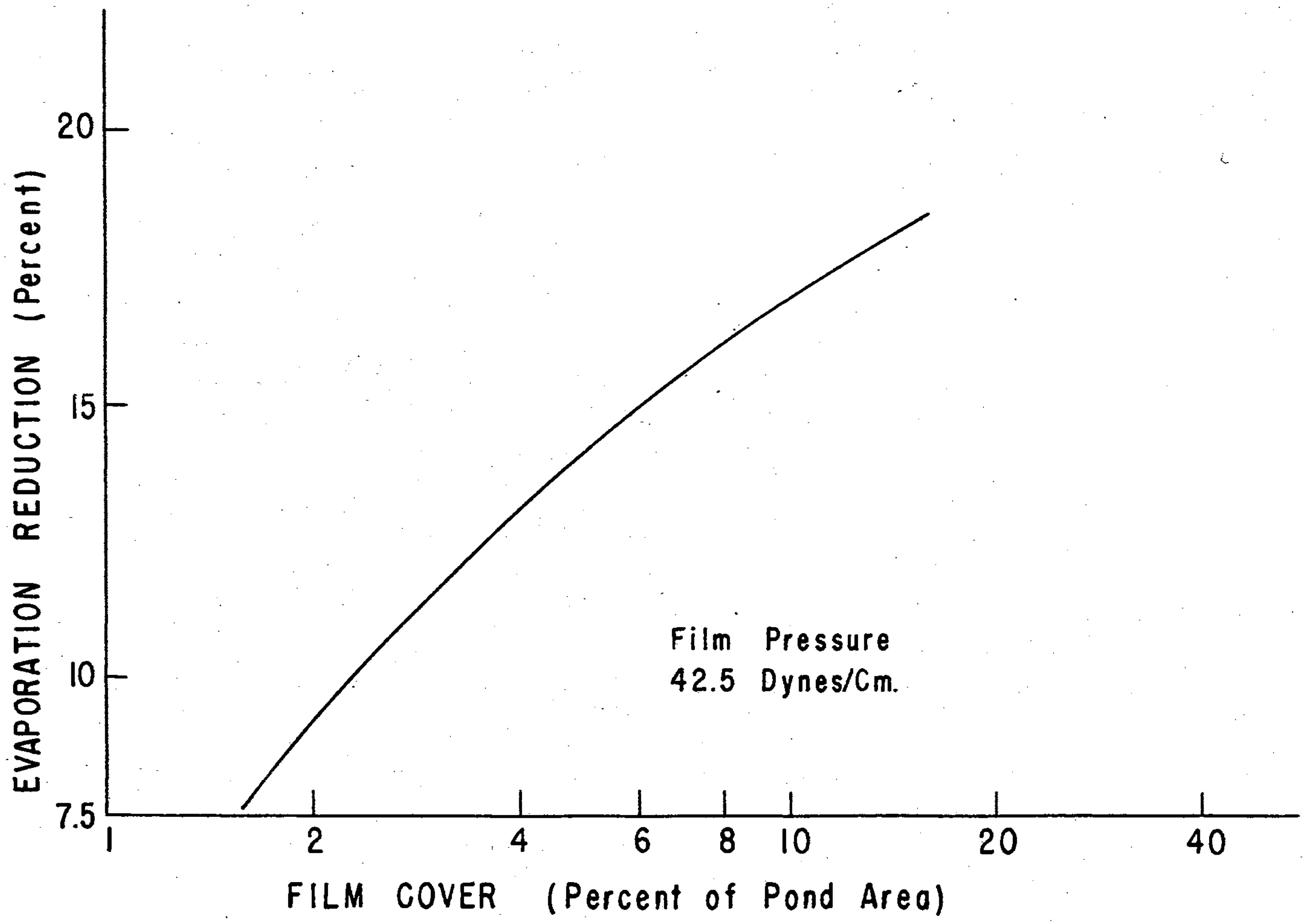


Figure 16. Effect of Film Area on Evaporation Reduction

it is plotted as rectangular coordinate while in Figure 15 it is plotted on a logarithmic scale; therefore, the relation of Figure 16 is curved.

CHAPTER VI

CONCLUSIONS

1. The monthly Class "A" pan to pond evaporation coefficient varies considerably while the annual coefficient is relatively stable. The annual coefficient in this experiment was found to be 0.73 while the value recommended for general use is 0.70.

2. Daily evaporation from a reservoir may be predicted by the use of an empirical equation relating 24 hour averages of wind velocity, relative humidity and water surface temperature. Care must be taken to locate the anemometer at the reference level of the equation which in this experiment was 2 meters. The equation computed from data of this experiment has the values $E = 0.75 (1 + 0.017u)(e_o - e_a)$ where E is evaporation in inches per 24 hours, u is 24 hour average wind velocity in miles per hour and $(e_o - e_a)$ is 24 hour average vapor pressure difference between the water surface and the air in pounds per square inch.

3. Monomolecular film sources and application methods used in this experiment failed to produce significant evaporation reduction. The raft application method was least effective; solution was second best; while direct powder application gave the best results. The formation of a dirt and biological coating on the pellet-

ized film source rendered it ineffective. The film source must remain in an active state as long as it is on the water surface if an effective film is to be produced.

4. Evaporation reduction due to a monomolecular film source decreases as wind velocity increases. This relation plots as a straight line on rectangular coordinate graph paper.

5. Film area decreases as wind velocity increases. This relation plots as a straight line on log-log graph paper. The equation relating per cent area of a compressed film and wind velocity on the experimental ponds has the values

$$A = \frac{668.39}{u^{2.707}}$$

6. Evaporation reduction may be predicted by the use of a derived curve relating per cent compressed film area and evaporation reduction. This curve applies only to the experimental ponds. A separate curve must be derived for each reservoir if the prediction is to be accurate.

CHAPTER VII

RECOMMENDATIONS FOR FURTHER STUDY

1. A rational approach to the wind velocity - film area relationship should be developed and tested. This approach would yield some reason for the effects noted in this experiment. This approach should be tested on both small and large reservoirs.
2. New methods of film application should be tested for more effective evaporation reductions. Possible methods are the use of a dispersion substance, continuous application, and recirculation of the film source.

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APPENDIX

APPENDIX A

SYMBOLS AND DIMENSIONS

Symbol	Dimensions	Description
e_a	$ML^{-1}T^{-2}$	Vapor pressure of air. (psi)
e_i	$ML^{-1}T^{-2}$	Vapor pressure of unmodified air. (mb)
e_o	$ML^{-1}T^{-2}$	Vapor pressure of saturated air at the temperature of the water surface. (mb or psi)
e_z	$ML^{-1}T^{-2}$	Vapor pressure of air at height z. (mb)
k_o		von Kármán's constant. (cm)
n		An empirical constant.
q		Specific humidity.
r	L	Radius of circular evaporating surface. (cm)
u	LT^{-1}	Average wind speed in horizontal direction (numerical subscript indicates height in meters)(cm/sec. or miles per hour)
u_*	LT^{-1}	Friction velocity, equal to $\sqrt{\tau/\rho}$.
z	L	Distance along vertical coordinate axis. (cm)
z_o	L	Roughness parameter. (cm)
A		Per cent area of pond covered by a film.
C_1		Experimental constant.
C_2		Experimental constant.
D	L^2T^{-1}	Molecular vapor diffusivity. (cm^2/sec.)
E	LT^{-1}	Evaporation per unit time. (in./24 hrs.)
F	$ML^{-2}T^{-1}$	Evaporation per unit area.
K		Experimental constant.

APPENDIX A (Continued)

Symbol	Dimensions	Description
P	$ML^{-1}T^{-2}$	Atmospheric pressure. (mb)
R		Per cent evaporation reduction.
V	L^3T^{-1}	Volume of water evaporated in unit time. (cm^3/sec.)
Γ		The gamma function.
ν	L^2T^{-1}	Kinematic viscosity of air. (cm^2/sec.)
ρ	ML^{-3}	Density of air. (gm/cm^3)

APPENDIX B

Sample Data Sheet

EVAPORATION POND DATA SHEET

Expt. No.________
Date ______________________ Time ____________ Observer______________

I. METEOROLOGICAL DATA

Precipitation: (Rain) (Snow)_____Inches. Date_____Approx. Time______
Wind: Anemometer reading_____ miles. General Direction ___Est. Vel.___mph.
Air Temperature: Max._____°F. Time_____ Min._____°F. Time_____
Rel. Humidity: Max._____%. Time_____ Min._____%. Time_____

II. WATER SURFACE TEMPERATURES

West Pond: Max._____°F; Min._____°F; Present _____°F.
East Pond: Max._____°F; Min._____°F; Present _____°F.
Evap. Pan: Max._____°F; Min._____°F; Present _____°F.

III. WATER SURFACE ELEVATIONS

	WEST POND					EAST POND				
Gage Well										
Point Length										
Time Start										
Time Stop										
Gage Reading No.1										
2										
3										
4										
5										
6										
7										
8										
9										
10										
Total										
Average										
Av. Reading on (Date)										
Stage Change (Loss) (Gain)										
Rainfall Correction (-)										
Net (Loss) (Gain)										

IV. REMARKS____

APPENDIX C

SUMMARY OF DATA FROM EVAPORATION PAN AND PONDS

Date	Time	Rain (in.)	Evaporation Loss (inches)			Avg. Wind Vel./24Hrs. (Miles per Hour)	Average Water Surface Temp.	Average Daily		(e_o-e_a) psi.	West Pond Evaporation (inches/ 24 Hrs.)
			Pan	West	East			Temp.	R.H.		
March											
21	1640										
22	1700			0.084	0.076	3.9	52.0	44	85	0.0288	0.083
23	0900	0.60						45	77		
24								44	84		
25	1057	0.07		0.128	0.194			41	88		
26	0930			0.205	0.147	9.3	45.5	35	79	0.0316	0.213
27	0925			0.095	0.080	2.4	49.0	42	60	0.0686	0.095
28	1055		0.073	0.076	0.074	2.2	50.5	45	69	0.0562	0.071
29	0835		0.160	0.122	0.100	2.7	56.5	53	50	0.1130	0.135
30	0935		0.240	0.120	0.093	6.7	55.0	57	57	0.0920	0.115
31											
April											
1	0835	0.29									
2	0840		0.027	0.099	0.089	5.3	59.0	54	81	0.0469	0.099
3											
4	0810	0.72									
5	0825			0.227	0.246	8.5	53.5	41	58	0.0851	0.225
6	0840		0.338	0.238	0.223	7.7	51.5	46	50	0.0936	0.236
7	1600		0.494	0.203	0.217	10.7	55.0	63	43	0.1220	0.156
8	0830	0.07									
9	0905			0.152	0.154	4.4	59.0	45	52	0.1186	0.149
10	0827		0.391	0.170	0.151	4.5	57.0	53	46	0.1242	0.174
11	0850		0.244	0.144	0.121	4.3	58.0	57	53	0.1120	0.148
12											

APPENDIX C (Continued)

Date	Time	Rain (in.)	Evaporation Loss (inches) Pan	West	East	Avg. Wind Vel./24Hrs. (Miles per Hour)	Average Water Surface Temp.	Average Daily Temp.	R.H.	$(e_o - e_a)$ psi.	West Pond Evaporation (inches/ 24 Hrs.)
April											
13	0817	0.06									
14											
15	0850		0.292	0.266	0.246						
16	0825	T	0.101	0.045	0.025						
17	0845	T									
18											
19											
20											
21											
22											
23											
24											
25											
26											
27											
28											
29											
30											
May											
1											
2	0842	0.09	0.096	0.079	0.074	4.0					
3	0840	0.89									
4	1007	0.08	0.156	0.281	0.291	6.4					
5											
6	0830		0.413	0.431	0.390	3.0	58.5	54	63	0.0898	0.222
7	0827		0.241	0.193	0.170	2.4	66.5	61	58	0.1351	0.193

APPENDIX C (Continued)

Date	Time	Rain (in.)	Evaporation Loss (inches)			Avg. Wind Vel./24Hrs. (Miles per Hour)	Average Water Surface Temp.	Average Daily		(e_o-e_a)	West Pond Evaporation (inches/ 24 Hrs.)
			Pan	West	East			Temp.	R.H.	psi.	
May											
8	0830		0.322	0.260	0.272	5.5	65.0	64	62	0.1161	0.260
9	0842	0.16	0.240	0.233	0.063						
10	0900		0.296	0.136	0.130	5.2	66.5	69	74	0.0836	0.134
11	1005	0.70									
12	0755	0.69									
13	0940	0.60									
14	0817		0.281	0.246	0.250	5.9	67.5	67	64	0.1199	0.240
15	0820		0.310	0.200	0.180	3.2	70.0	72	60	0.1091	0.200
16											
17											
18											
19											
20											
21											
22		0.48									
23	0820		0.050	0.119	0.111	5.6					
24	0835	T	0.157	0.146	0.150	3.3					
25	0900	0.83									
26	0758		0.301	0.173	0.157	4.3					
27	0840		0.293	0.188	0.182	1.9	74.0	70	58	0.1744	0.184
28	0830		0.223	0.169	0.159	1.7	75.5	72	68	0.1399	0.170
29	0820		0.234	0.213	0.205	3.7	74.0	71	71	0.1204	0.212
30	1445	1.27									
31	1610		0.086	0.111	0.105	3.3	75.0	68	86	0.0601	0.107
June											
1		0.40									

APPENDIX C (Continued)

Date	Time	Rain (in.)	Evaporation Loss (inches) Pan	West	East	Avg. Wind Vel./24Hrs. (Miles per Hour)	Average Water Surface Temp.	Average Daily Temp.	R.H.	(e_o-e_a) psi.	West Pond Evaporation (inches/ 24 Hrs.)
June											
2											
3											
4											
5											
6											
7	0900		0.336	0.211	0.198	4.5					
8	1007		0.355	0.266	0.272	6.9					
9	1132	0.03									
10	0810	1.73									
11	0910		0.253	0.133	0.118	9.1					
12	0930	0.30									
13	1000	0.05									
14	0930	T	0.304	0.203	0.188	3.7					
15	0915			0.251	0.231	8.0					
16	0750		0.380	0.310	0.334	13.0					
17	0925		0.417	0.332	0.309	12.6					
18	0945	2.25									
19	0930			0.263	0.224	6.1					
20	0925		0.307	0.241	0.246	4.4					
21	0935		0.358	0.284	0.286	8.9	78.5	78	70	0.1447	0.283
22											
23											
24	1010	2.33									
25	0930		0.275	0.203	0.207	4.5	77.5	72	70	0.1400	0.200
26	1325	0.27									
27	2250		0.138	0.146	0.140	6.3	74.5	73	94	0.0253	0.109
28	0950	0.89									

APPENDIX C (Continued)

Date	Time	Rain (in.)	Evaporation Loss (inches) Pan	West	East	Avg. Wind Vel./24Hrs. (Miles per Hour)	Average Water Surface Temp.	Average Daily Temp.	R.H.	$(e_o - e_a)$ psi.	West Pond Evaporation (inches/ 24 Hrs.)
June											
29	0805		0.266	0.155	0.158	4.7	80.0	80	79	0.1064	0.157
30	0840		0.318	0.205	0.206	8.5	81.0	86	79	0.1100	0.201
July											
1	1020	0.88									
2	0918			o.134	0.144	4.8	84.0	85	90	0.0577	0.137
3	0915		0.361	0.202	0.207	4.4	88.0	89	79	0.1377	0.202
4	0855		0.448	0.398	0.413	7.4	86.0	89	63	0.2277	0.405
5	0925		0.449	0.415	0.412	7.1	82.5	81	70	0.1649	0.432
6	0820		0.334	0.302	0.292	5.1	82.0	79	63	0.2001	0.315
7	0845		0.372	0.294	0.279	8.4	81.5	86	75	0.1328	0.303
8	0945		0.463	0.401	0.385	9.5	82.0	88	67	0.1785	0.385
9	0915		0.255	0.199	0.204	6.8	82.5	88	74	0.0889	0.203
10	0925		0.326	0.254	0.251	5.1	85.0	87	73	0.1609	0.253
11	0935		0.342	0.271	0.269	5.5	85.0	88	77	0.1371	0.270
12	0950		0.402	0.318	0.324	7.5	85.0	89	65	0.2086	0.316
13	0825		0.396	0.346	0.350	6.7	83.5	89	62	0.2158	0.353
14	0830		0.412	0.310	0.317	5.4	85.0	90	65	0.2086	0.309
15	0915		0.421	0.306	0.315	5.1	86.0	90	68	0.1969	0.297
16	0920		0.455								
17	0910		0.455	0.327	0.336	6.4	83.5	89	61	0.2215	0.328
18	0920		0.443	0.340	0.345	6.3	83.5	90	64	0.2045	0.339
19											
20											
21											
22	0950										
23	0920	T		0.217	0.217						

APPENDIX C (Continued)

Date	Time	Rain (in.)	Evaporation Loss (inches) Pan	West	East	Avg. Wind Vel./24Hrs. (Miles per Hour)	Average Water Surface Temp.	Average Daily Temp.	R.H.	$(e_o - e_a)$ psi.	West Pond Evaporation (inches/ 24 Hrs.)
July											
24	0915		0.329	0.248	0.249	5.8	84.5	84	81	0.1115	0.249
25	0925		0.219	0.198	0.201	5.3	83.0	84	79	0.1173	0.197
26	0855	0.29	0.198	0.118	0.108						
27	0825		0.336	0.241	0.256	6.4	83.0	87	69	0.1732	0.246
28	0830		0.472	0.343	0.379	7.4	83.5	89	58	0.2386	0.342
29	0830		0.457	0.322	0.348	5.6	84.5	90	53	0.2757	0.322
30	0945		0.461	0.306	0.312	5.9	85.5	92	65	0.2120	0.297
31	0905		0.410	0.295	0.325	6.0	85.5	86	73	0.1635	0.304
August											
1	1020		0.332	0.230	0.241	3.1	86.5	87	67	0.2063	0.218
2	0900		0.336	0.217	0.238	3.1	87.5	83	60	0.2582	0.230
3	0945			0.322	0.302	4.8	87.5	91	62	0.2453	0.312
4	0705	1.37				5.7					
5	1125			0.400		7.1	83.5	79	82	0.1022	0.339
6	1030		0.084	0.175	0.142	5.0					
7	0820		0.327	0.293	0.300	5.5					
8	0820		0.361	0.337	0.342	6.2	79.5	78	65	0.1745	0.337
9	0850		0.377	0.306	0.312	7.4	79.0	83	67	0.1618	0.300
10	0830		0.410	0.253	0.264	6.5	80.0	85	61	0.1976	0.257
11	0725		0.369	0.226	0.223	4.9	82.0	86	67	0.1785	0.236
12	0840		0.333	0.206	0.206	4.1	84.5	86	75	0.1466	0.194
13	0930		0.359	0.231	0.244	4.2	86.5	89	65	0.2188	0.222
14	0825		0.456	0.332	0.321	6.1	84.0	92	53	0.2713	0.346
15	0915		0.233	0.220	0.210	5.6	83.0	88	69	0.1732	0.212
16	0825		0.250	0.222	0.208	6.5	82.0	84	86	0.0757	0.231
17	0830	0.26		0.225	0.209	6.7					

APPENDIX C (Continued)

Date	Time	Rain (in.)	Evaporation Loss (inches)			Avg. Wind Vel./24Hrs. (Miles per Hour)	Average Water Surface Temp.	Average Daily		(e_o-e_a)	West Pond Evaporation (inches/ 24 Hrs.)
			Pan	West	East			Temp.	R.H.	psi.	
August											
18											
19	0845	0.10		0.346	0.339	5.2					
20	0825		0.289	0.167	0.163	2.7	81.5	81	67	0.1753	0.169
21											
22											
23	1100					8.1					
24	0855		0.366	0.264	0.251	7.9	78.5	83	70	0.1447	0.288
25	0750		0.340	0.239	0.203	4.6	79.5	80	67	0.1645	0.249
26	0850		0.398	0.239	0.268	5.3	79.0	85	56	0.2157	0.229
27	1120		0.475	0.339	0.302	7.1	78.5	89	46	0.2604	0.296
28	0935		0.481	0.375	0.368	8.8	78.0	88	53	0.2230	0.408
29	0825		0.428	0.277	0.247	7.0	78.5	86	61	0.1881	0.289
30	0825		0.451	0.321	0.296	6.9	78.5	86	56	0.2122	0.321
31	0825		0.421	0.269	0.243	6.0	79.5	85	63	0.1844	0.269
September											
1	0650	0.07	0.248			5.3					
2	0850		0.379	0.228	0.199	5.6	79.0	87	59	0.2010	0.211
3	1030		0.540	0.382	0.348	6.0	78.5	85	44	0.2701	0.357
4	0820	0.04	0.333	0.239	0.233	5.5					
5	0825			0.240	0.214	4.5					
6	0815	0.12		0.130	0.129	4.8					
7	0835			0.346	0.355	8.3					
8											
9	0812			0.391	0.351	4.2					
10	0815			0.197	0.159	4.9	72.0	73	60	0.1553	0.197
11	0835	0.03	0.367	0.234	0.242	9.0					

APPENDIX C (Continued)

Date	Time	Rain (in.)	Evaporation Loss (inches)			Avg. Wind Vel./24Hrs. (Miles per Hour)	Average Water Surface Temp.	Average Daily		$(e_o - e_a)$	West Pond Evaporation (inches/ 24 Hrs.)
			Pan	West	East			Temp.	R.H.	psi.	
September											
12	1425	1.41									
13	0911		0.070	0.060	0.031	1.8	72.0	64	85	0.0582	0.076
14	1030	1.81									
15											
16	1310	0.88									
17	0935		0.218	0.107	0.090	3.5	71.0	71	70	0.1126	0.121
18	1005		0.242	0.157	0.140	5.5	72.0	73	75	0.0971	0.154
19	0930		0.236	0.132	0.129	7.2	72.5	76	81	0.0750	0.136
20	0925		0.260	0.163	0.169	6.2	75.5	75	84	0.0700	0.164
21	0950	0.01	0.192	0.171	0.181	7.3					
22											
23	0830		0.270	0.331	0.342	5.3					
24	0915		0.180	0.151	0.101	2.7	69.5	72	63	0.1320	0.147
25	0817		0.217	0.157	0.150	3.8	69.5	69	72	0.0999	0.164
26	0912		0.116	0.132	0.125	4.4	68.0	69	76	0.0813	0.127
27	0812		0.152	0.104	0.125	3.5	70.5	70	76	0.0886	0.109
28	0903		0.219	0.145	0.143	4.8	69.5	69	75	0.0892	0.140
29											
30	0815		0.373	0.290	0.269	2.6					
October											
1	0915		0.174	0.130	0.093	2.3	71.0	68	57	0.1430	0.125
2	0825		0.235	0.170	0.142	3.7	70.0	72	56	0.1596	0.176
3	0910		0.246	0.181	0.169	4.8	69.5	71	63	0.1320	0.176
4	0835		0.249	0.185	0.183	6.7	70.5	73	69	0.1144	0.189
5	0905		0.246	0.153	0.143	7.4	70.0	75	76	0.0871	0.150
6	0825		0.214	0.161	0.156	5.6	70.5	73	72	0.1033	0.160

APPENDIX C (Continued)

Date	Time	Rain (in.)	Evaporation Loss (inches) Pan	Evaporation Loss (inches) West	Evaporation Loss (inches) East	Avg. Wind Vel./24Hrs. (Miles per Hour)	Average Water Surface Temp.	Average Daily Temp.	Average Daily R.H.	(e_o-e_a) psi.	West Pond Evaporation (inches/ 24 Hrs.)
October											
7	0825		0.214	0.161	0.156	5.6	70.5	73	72	0.1033	0.160
8	1120	0.29									
9											
10	0910	0.04									
11	0930			0.113	0.092	3.3	64.5	56	81	0.0570	0.112
12	1005		0.137	0.104	0.085	5.6	63.0	63	80	0.0570	0.102
13											
14	1334	0.45									
15	1110	T									
16	1007		0.051	0.016	0.005	3.4	61.5	67	96	0.0108	0.015
17	0907		0.143	0.102	0.085	5.7	62.5	63	90	0.0280	0.106
18	1119			0.175	0.175	5.4	62.0	57	72	0.0770	0.161
19	0933			0.122	0.113	3.7	60.5	55	61	0.1017	0.132
20											
21	0840			0.273	0.246	4.5					
22											
23	1052	1.00									
24	1140			0.266	0.263	13.1	57.0	59	82	0.0414	0.258
25	0929			0.139	0.162	9.6	53.0	50	93	0.0139	0.128
26	0841			0.218	0.195	9.1	46.5	36	90	0.0156	0.255
27	0721			0.128	0.106	5.9	44.5	36	79	0.0304	0.138
28	0940			0.075	0.049	3.6	46.0	39	72	0.0429	0.068
29	1000		0.159	0.118	0.113	7.4	46.0	49	56	0.0674	0.116
30	0940			0.029	0.015	3.2	46.5	51	74	0.0406	0.029
31	0910			0.052	0.033	4.0	50.5	54	65	0.0635	0.053

APPENDIX C (Continued)

Date	Time	Rain (in.)	Evaporation Loss (inches) Pan	West	East	Avg. Wind Vel./24Hrs. (Miles per Hour)	Average Water Surface Temp.	Average Daily Temp.	R.H.	(e_o-e_a) psi.	West Pond Evaporation (inches/ 24 Hrs.)
November											
1	0852	T		0.011	0.004						
2	0857	0.05									
3											
4	0833	0.31		0.247		8.4					
5											
6	0914	0.19		0.088		6.2					
7											
8	0834	0.62									
9	0901			0.137	0.121	5.6	48.0	38	68	0.0529	0.135
10											
11	0835			0.199	0.180	5.3					
12											
13	0820	1.34									
14	1108	0.04									
15	0823										
16	0836		0.140	0.076	0.070	6.0	50.0	52	78	0.0392	0.075
17											
18	0815	0.10	0.153	0.133	0.135	9.4					
19	0916		0.065	0.158	0.171	9.4	43.5	34	78	0.0307	0.152
20	0833		0.065	0.068	0.057	5.1	42.5	42	69	0.0416	0.070
21	0909			0.081	0.076	5.4	42.5	41	71	0.0389	0.079
22	0852		0.082	0.092	0.086	5.4	41.5	37	71	0.374	0.090
23	0834		0.074	0.048	0.041	2.5	40.0	30	76	0.0292	0.049
24	1555		0.074	0.078	0.071	4.8	40.0	38	55	0.0548	0.060
25	0846		0.015	0.020	0.012	3.4	41.5	41	80	0.0258	0.028
26	1111		0.116	0.013	0.009	5.2	42.0	52	66	0.0447	0.012
27	0830		0.191	0.067	0.061	8.7	45.5	56	59	0.0617	0.075

APPENDIX C (Continued)

Date	Time	Rain (in.)	Evaporation Loss (inches) Pan	West	East	Avg. Wind Vel./24Hrs. (Miles per Hour)	Average Water Surface Temp.	Average Daily Temp.	R.H.	(e_o-e_a) psi.	West Pond Evaporation (inches/ 24 Hrs.)
November											
28	0819		0.111	0.097	0.108	8.9	44.5	43	82	0.0261	0.098
29	0854		0.103	0.081	0.065	5.6	43.5	40	59	0.0572	0.079
30	0847	0.07		0.111	0.115	10.8					
December											
1											
2	0835			0.141	0.125	5.4					
3	0921			0.113	0.088	9.8	38.5	46	56	0.0505	0.110
4	0837		0.078	0.062	0.074	5.6	40.0	40	72	0.0341	0.064
5	0925		0.153	0.077	0.067	6.1	40.5	50	40	0.0745	0.074
6	0827		0.301	0.147	0.144	16.6	41.5	56	40	0.0774	0.154
7	0837		0.122	0.052	0.064	11.9	44.5	46	78	0.0319	0.052
8											
9	0821		0.278	0.289	0.278	10.8					
10											
11											
12											
13											
14											
15											
16	1326	T									
17											
18											
19											
20	0925	0.02	0.285	0.182	0.153	10.7					
21											
22											

APPENDIX C (Continued)

Date	Time	Rain (in.)	Evaporation Loss (inches)			Avg. Wind Vel./24Hrs. (Miles per Hour)	Average Water Surface Temp.	Average Daily		(e_o-e_a) psi.	West Pond Evaporation (inches/ 24 Hrs.)
			Pan	West	East			Temp.	R.H.		
December											
23	0902			0.206	0.194	8.6					
24											
25											
26											
27	1010	0.96									
28											
29											
30	0830			0.492	0.527	6.1					
31	1134	T	0.065	0.104	0.102	10.0					
January											
1											
2	0831			0.160	0.143	5.7					
3											
4	1542			0.161	0.157	5.9					
5											
6	0819			0.078	0.069	4.5					
7											
8											
9	1625			0.268	0.280	8.2					
10											
11											
12											
13	1134	0.25									
14											
15											
16	1515	T									

APPENDIX C (Continued)

Date	Time	Rain (in.)	Evaporation Loss (inches) Pan	West	East	Avg. Wind Vel./24Hrs. (Miles per Hour)	Average Water Surface Temp.	Average Daily Temp.	R.H.	(e$_o$-e$_a$) psi.	West Pond Evaporation (inches/ 24 Hrs.)
January											
17											
18	1132			0.098	0.083	5.4					
19											
20											
21											
22	1705	0.95									
23											
24											
25	1130			0.041	0.047	4.7					
26											
27	1145			0.149	0.146	6.7					
28	1110	0.02		0.039	0.036	3.8					
29											
30	1120			0.087	0.085	5.1					
31											
February											
1	1316		0.298	0.223	0.222	10.1					
2											
3											
4	1130			0.246	0.234	9.6					
5											
6											
7	1340	0.36									
8											
9											
10											

APPENDIX C (Continued)

Date	Time	Rain (in.)	Evaporation Loss (inches)			Avg. Wind Vel./24Hrs. (Miles per Hour)	Average Water Surface Temp.	Average Daily		(e_o-e_a) psi.	West Pond Evaporation (inches/ 24 Hrs.)
			Pan	West	East			Temp.	R.H.		
February											
11											
12											
13											
14											
15											
16											
17											
18											
19											
20											
21	0915	T									
22											
23											
24	0907										
25	1008		0.155	0.024	0.027	4.5	50.5	57	77	0.0417	0.023
26	0825	0.02									
27											
28											
March											
1	0850	0.32									
2											
3	0852			0.165	0.149	5.8					
4	1045			0.063	0.052	4.4	37.5	37	76	0.0265	0.058
5	0827	T		0.040	0.046	7.4					
6	1027										
7	0845	0.80									

APPENDIX C (Continued)

Date	Time	Rain (in.)	Evaporation Loss (inches)			Avg. Wind Vel./24Hrs. (Miles per Hour)	Average Water Surface Temp.	Average Daily		(e_o-e_a) psi.	West Pond Evaporation (inches/ 24 Hrs.)
			Pan	West	East			Temp.	R.H.		
March											
8											
9											
10	1310	0.95									
11											
12											
13											
14	0854	0.35									
15	0858			0.089	0.089	6.2	38.5	36	65	0.0401	0.089
16											
17											
18											
19	0843	0.44									
20	1009			0.058	0.056	4.8	40.0	39	75	0.0304	0.055
21	0911		0.123	0.058	0.066	5.5	45.0	44	59	0.0605	0.061
22	1023		0.179	0.066	0.066	9.4	44.5	52	61	0.0565	0.063
23											
24	1301	0.92									
25	1004		0.167	0.106	0.108	9.9	46.0	47	72	0.0429	0.121
26	0947		0.061	0.058	0.060	7.0	45.5	44	88	0.0180	0.059
27	1007		0.096	0.107	0.103	6.0	45.5	40	87	0.0195	0.106
28	0819		0.152	0.072	0.068	4.2	49.0	46	64	0.0617	0.078
29	0830	1.05									
30											
31	0909	T	0.243	0.192	0.196	8.0					

APPENDIX D

WIND VELOCITY - EVAPORATION REDUCTION RELATIONS

Test Number	Dates, 1957	Equation	Correlation Coefficient	Range in Avg. Wind Velocity
1	May 6-15	$R = 24.99 - 4.605u$	-0.941	2.4 - 5.9
2	May 23-31	$R = 82.92 + 1.005u$	0.342	1.7 - 5.6
3	June 7-21	$R = 8.48 - 0.521u$	-0.199	3.7 - 13.0
5	July 9-18	$R = 2.10 - 0.573u$	-0.388	5.1 - 7.5
7	Aug. 6-20	$R = 3.03 - 0.08u$	-0.003	2.7 - 7.4
8	Aug. 23 - Sept. 10	$R = 20.39 - 1.937u$	-0.498	4.4 - 9.0
9	Sept. 16-30	$R = 49.63 - 7.729u$	-0.773	2.7 - 7.4
10	Sept. 30 - Oct. 7	$R = 47.52 - 6.663u$	-0.905	2.3 - 7.3
11	Oct. 19 - Nov. 11	$R = 66.77 - 6.589u$	-0.671	3.0 - 13.8
12	Nov. 22 - Dec. 9	$R = 33.99 - 2.839u$	-0.486	2.5 - 17.3

VITA

Harold Sattler

Candidate for the Degree of

Master of Science

Thesis: EVAPORATION AND ITS SUPPRESSION WITH HEXADECANOL AND OCTADECANOL FILMS ON PAIRED PONDS AT STILLWATER, OKLAHOMA

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