A WIND TUNNEL INVESTIGATION OF AIR FLOW OVER A HEXADECANOL MONOLAYER SPREAD ON A WATER SURFACE

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PREFACE

Effect of forces due to air flow over a hexadecanol film spread in a monolayer over a water surface is of interest in the design of systems and structures to maintain film coverage on an outdoor water surface. This dissertation deals with film coverage under controlled air flow conditions. Influence of barrier size and shape were investigated. It is hoped that this contribution to solving the problem of maintaining hexadecanol film on a water surface will assist investigatiors in more completely designing future research projects.

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CHAPTER I

INTRODUCTION

Statement of Problem

Scientific investigations in the late nineteenth century led to the discovery that certain materials formed a layer a single molecule thick when placed on a water surface. Extensive studies of monolayer forming compounds were conducted during the first thirty years of the twentieth century. Of specific interest was the group that showed the ability to decrease evaporation from water surfaces. Hexadecanol[1]--cetyl alcohol-- was among the monolayers that showed promise as an effective and practical evaporation retardant. Scientists were beginning to seek ways of utilizing these compounds on large outdoor storage reservoirs by the middle of the twentieth century. Several field projects and supporting laboratory studies were initiated to hasten the gathering of data on which to base operating procedures.

Laboratory work had shown that over 50 percent of the water usually lost by evaporation was saved when suitable monolayers were spread over the water surface. Results from field tests were not as promising. Wind action removed the monolayer film from the surface of lakes. The problem of maintaining film coverage was presented. Solution of

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[1]The names hexadecanol and cetyl alcohol may be used interchangeably throughout this writing.

this problem depended on determining the relationship between air velocities and film coverage. Nearly steady state conditions--such as can be obtained in a wind tunnel--were necessary to establish the effect of wind on film coverage.

In field trials the problem of film removal was combatted by continual application of hexadecanol to replenish the film. Chemical dispensers were installed at strategic locations around the reservoir being treated. The type of dispenser depended on the hexadecanol condition--solid or liquid. If liquid, heaters and insulated containers were necessary. Dusting of the dry powder required special equipment. Mixing the powder with water to form a slurry used pumps and a pipe distribution system. Each presented special difficulties but all had the common problem of controlling the system so hexadecanol would be dispensed at the upwind edge of the reservoir and in quantities demanded by varying wind speeds. At velocities over 18 mph, wave action destroyed the film even though hexadecanol was continually applied.

A second means of maintaining film coverage was by reducing the size of the area covered and providing protection against the wind. This was accomplished on small reservoirs--100 x 120 feet--by dividing the surface into compartments 14.5 feet square. Floating barriers were used so the projection above the surface could be varied. Problems associated with this method were: application of the film, maintenance of the barriers, and height, location, and configuration of the barrier.

Time required for outdoor studies because of uncontrollable weather conditions and the work necessary to change elevation of the barriers limited conditons under which tests could be conducted.

Fluctuating air velocities were not conducive to measurements related to a particular windspeed. Methods used to indicate presence and strength of the hexadecanol film did not give the location of the film edge at high velocities.

The above problems, which are inherent in outdoor studies, can be controlled to a greater degree in the laboratory. This suggested that an investigation of monolayer film coverage, with and without barriers, be conducted. A laboratory study was selected to enable setting up many possible combinations in a short period of time.

Objectives

The objectives of this investigation were:

1. To develop a prediction equation relating the length of a hexadecanol film covering a water surface to the wind shear force that acts on the film.
2. To investigate the influence of barriers in maintaining a hexadecanol film on a water surface.

Scope of the Investigation

This investigation was a laboratory study using a 4 foot x 4 foot x 50 foot wind tunnel to provide the necessary air flow. The reasons for this selection were to obtain steady air flow conditions, to control water temperature, and to enable gathering data in spite of adverse outdoor weather. Small sized barriers were more easily handled. This made it possible to install barriers having different heights, angles of inclination, amounts of perforation, and position of perforation. Change of distance between barriers was readily accomplished.

Edge effects due to a narrow reservoir were assumed negligible and development of an air flow profile in the wind tunnel similar to that expected in the field was assumed to produce data that were indicative of field results.

The tunnel size placed a restriction on the length and width of the reservoir. Sufficient space was needed upwind from the reservoir to permit development of an air flow pattern similar to outside flow conditions and to insert barriers and instrumentation. Equipment and material with which to construct the reservoir were influencing factors. With the selection of a reservoir 32 inches wide and 24 feet long, the range of air velocities was restricted. The film was necessarily drawn away from the upwind edge of the reservoir. Minimum wind speed was that velocity required to accomplish the reduction of film coverage to less than the 24 foot length of the reservoir. Maximum velocity was determined by strength of the film. Heights of barriers were restricted by the vertical space in the wind tunnel. A barrier height of 6 inches was considered a maximum. Greater blockage was assumed to create an unrealistic flow pattern.

CHAPTER II

REVIEW OF LITERATURE

Background

A common experience of the western part of the United States has been too little water. Although not occurring as frequently in the eastern part of the United States, water shortages often cause a greater disruption of the economy because the population is not prepared to cope with the restrictions imposed.

Secretary of Agriculture Benson (1955) stated:

> I have little need to remind you that water has become one of our major national concerns.
>
> Nearly everyone in this country in the past few years has experienced some problem caused by too much water when we do not want it or too little water when we do want it.

Frank (1955) pointed out that throughout the ages people have either chosen, or been compelled, to settle in areas where water was deficient in amount, inferior in quality, or erratic in behavior. This closely describes the condition in the Southwest.

As a result, large dams were constructed to impound water for major agricultural uses. Numerous smaller dams and excavated reservoirs were built to provide water for livestock and household uses in rural areas. This method of conserving runoff waters created large areas of free water surfaces. A new water loss was created--evaporation of water into the atmosphere. For many years this tremendous loss was largely ignored. Some people recognized that this loss existed but little effort was expended to reduce the loss. More serious thought has been given to this problem in the last fifteen years.

Realization of the magnitude of evaporation losses brought about studies to obtain best estimates of these losses. The Lake Cachuma report (1961) gave an estimate of 25 million acre feet of water lost annually by evaporation in the western states. The United States Department of Interior (1962) reported an annual water loss of 16,000 acre feet from Lake Cachuma reservoir. Harbeck (1959) stated the annual gross evaporation from Lake Mead, the nation's largest reservoir, ranged from 699,000 to 875,000 acre feet from 1953 to 1956. This water loss from a single reservoir exceeded the total storage capacity of most lakes in the United States. Crow and Daniel (1958) stated that water losses from Lake Carl Blackwell in Oklahoma totaled 69.4 inches—over four times the withdrawal for use by a city of 20,000 people. The same paper reported that for a small pond with a surface area varying from 1 acre to 0.3 acre during the study period, the evaporation loss was 42.39 inches compared to 3.42 inches for household uses. Evaporation losses were over 12 times consumptive use.

Monolayer Characteristics

Studies basic to the problem of evaporation control were related to monolayer films and were carried out in the field now known as physical chemistry. The first published information known to the writer was a letter to Lord Rayleigh from Pockels (1891) which read as follows:

> First I will describe a simple method, which I have employed for increasing or diminishing the surface of a liquid in any proportion, by which its purity may be altered at pleasure.
>
> A rectangular tin trough, 70 cm. long, 5 cm. wide, 2 cm. high, is filled with water to the brim, and a strip of tin

about 1 1/2 cm. wide laid across it perpendicular to its length, so that the underside of the strip is in contact with the surface of the water, and divides it into two halves. By shifting this partition to the right or left, the surface on either side can be lengthened or shortened in any proportion, and the amount of the displacement may be read off on a scale held along the front of the trough.

Upon the purity of the surface depends its mobility, and in consequence the persistence of a wave once set in motion.

Every solid body, however clean, which is brought in contact with a newly formed surface, contaminates it more or less decidedly, according to the substance of which the body consists. With many substances, such as camphor flour, this effect is so strong that the tension of the surface is lowered a definite value; with others (glass, metals) it is only shown by the increase of relative contamination. The contaminating current which goes out from the circumference of a body--for example, of a floating fragment of tin foil--is easily made visible by dusting the water with Lycopodium or flowers of sulpher. I will call it, for the sake of brevity, "the solution current". The solution of a body which is introduced into a perfectly clean water surface lasts until the relative contamination produced by it has attained a definite value, which is different for every substance.

This letter established the fact that if certain immiscible substances were placed on a water surface in small amounts, that substance would spread until a thin film formed over part or all of the water surface. Additional amounts of the substance would continue to spread until a fully compressed film formed. Any subsequent application of the substance would not spread but remain at the point of application.

Harkins (1921) touched on the properties of monolayer films when he stated:

Langmuir considers all cohesional and adhesional forces as chemical, while van Laar has recently published the results of an extensive series of calculations which show that the square root of van der Waal's constant of attraction 'a' is additive, and therefore comes to the conclusion that all such forces are physical. The calculations by Einstein[3], Kleeman[4], and Clark[5], have also given coefficients of atomic attraction which are moderately exact constants.

Obvious disagreement existed among physical chemists concerning forces acting within a monolayer film. This disagreement was most pronounced between Harkins and Langmuir. Harkins (1939) stated:

> Among the aliphatic hydrocarbons the cohesional work (per unit area) increases about 3 ergs for each increase of one in the number of carbon atoms in the molecule from hexane to octane (Table VI). . . The cohesion is obviously due to van der Waal's forces, which are weaker for the iso-compounds.

This indicated that Harkins still held to the theory he set forth in 1921.

Adams (1930) reported:

> It is difficult to interpret the results of rigidity measurements on the film in terms of molecular forces, since the solid films are almost certainly, from the hasty manner in which they are formed, heterogeneous masses of very small and irregular two-dimensional crystals...........
>
> The insoluble films seem always to be one molecule thick, even if the area is diminished until there is no longer room for all the molecules in their closest possible packing, the film gives way by buckling locally and expelling enormous numbers of molecules to form a ridge, the rest of the monomolecular film being unchanged. A uniform second layer of molecules above the first has never been found with insoluble films.

Hexadecanol Properties

Langmuir and Langmuir (1927) reported on pertinent characteristics of hexadecanol. The melting point was about 50°C; therefore, at temperatures commonly encountered on water reservoirs the molecules of the film are solid. Observation of the film showed that the monolayer performed as a liquid at temperatures as low as 4°C.

Commenting on physical properties of hexadecanol, Langmuir (1927) stated:

> The mechanical properties of these films indicate clearly that they can exist in either the liquid or the solid state. For example, films of fatty acids on water which is slightly alkaline are definitely solid as is seen

by the fact that when they are under even a very small external pressure they can withstand considerable shearing stresses. On the other hand, a monomolecular film of cetyl alcohol, $C_{16}H_{33}OH$, on water behaves like a two dimensional liquid, for even under high surface compression it can be made to circulate freely by blowing on it gently.

Bikerman (1958) had this to say concerning a monolayer film of hexadecanol:

> It has been mentioned in #49 that some "condensed" films behave more like liquids and some more like solids. This is a classification according to the value of viscosity. "Solid" films are so viscous that dust particles (talc is generally used) do not move when placed on such films and subjected to a weak air blast (Devaux's method). Dust particles on a "liquid" film freely move about in the plane of the film.

In regard to the evaporation suppression ability, Langmuir and Langmuir (1927) said:

> The writers find that a monomolecular film of cetyl alcohol opposes a resistance of 65,000 to the evaporation of water, so that the effect on the evaporation is readily observed in experiments at atmospheric pressure.

Nutting and Harkins (1939) reported that the average cross-sectional area of the hexadecanol molecule was 21.85 $\pm$(0.25%)Å. This was in close agreement with Langmuir's (1917) measurement of 21 x 10^{-16} sq cm. Langmuir (1917) also noted that there was no significant change of film characteristics from 4°C to 50°C.

Timblin (1957) stated that the ability of a monolayer to reduce evaporation depended on its degree of compression. Greater compression produced better evaporation reducing abilities. Film pressure below 40 dynes/cm was reported as a dividing point. Higher pressures did not reduce the evaporation rate appreciably, but as the pressure decreased from the 40 dynes/cm level the evaporation rate began to increase noticeably.

Michel (1962) touched on the subject of film compression. He pointed out that no satisfactory method had been developed for measuring surface tension of a monolayer on an outside water reservoir. It was his opinion that tension ring devices and piston oils were too sensitive. However, other investigators do accept the use of piston oils as a measuring method. Photography detected the presence of a monolayer but did not indicate the degree of compression. The damping of ripples did not assure the presence of a completely compressed monolayer (Florey, Foster, and Townsend, 1959).

Timblin (1957) reported on the use of indicator oils, or piston oils, as they are frequently referred to in English and Australian papers. These oils were prepared according to a formula used by Adams. When tested under temperature ranges normally encountered in the field, it was determined that the results would be accurate within ± 2 1/2 dynes/cm. This was considered reasonably accurate for field studies.

Another observation from the above study was the forming of a dodecyl alcohol monolayer when a drop of this indicator oil was used near the shore line. All studies in the wind tunnel would be under conditions similar to tests near the shore and contamination of the desired monolayer would be expected. Preliminary tests showed this to be the case and a major problem was encountered in cleaning up equipment for subsequent tests. The above showed that indicator oils were not satisfactory for a wind tunnel study.

Applicable Fluid Mechanics

The field of fluid mechanics was developing at the same time the physical chemists were investigating monolayer behavior. Reynolds (1883) showed that to obtain similarity in certain fluid mechanic studies, it was necessary to combine the quantities of length, velocity, viscosity and density into a dimensionless number. This combination, now known as Reynolds Number, was

$$Re = \frac{\text{density x velocity x length}}{\text{viscosity}}$$

In research involving fluid flow, the quantities making up Reynolds Number must be considered. Inertial forces may become predominant at high values of Reynolds Number and the drag becomes constant.

Closely associated with this relationship was the boundary layer theory developed largely by Prandtl (1904) and studied extensively by Tietjins and Schlichting. This concept was evolving about 1904. The momentum theory, developed analytically for laminar flow, showed a relationship between the shear on an object and the flow of a fluid past the object. Of interest to the study discussed in this dissertation was the flow over flat plates. Shear due to laminar flow over a flat surface is given by the equation

$$T = .323\rho V^2(\mu/\rho Vx)^{1/2}$$

Where

T = shear stress

ρ = air density

V = air velocity

μ = air viscosity

x = significant length--dependent upon the particular system.

Turbulent values cannot be obtained directly but Blasius (1959) experimentally determined a value for shear based on boundary layer thickness. This relationship was

$$T = 0.0228\rho V^2(\mu/\rho V\delta)^{1/4}$$

where terms are the same as defined above except

δ = boundary layer thickness

When equated to the momentum integral and solved, the shear can be expressed as

$$T = 0.0296\rho V^2(\mu/\rho Vx)^{1/5}$$

This can be written as

$$T = 0.0296\rho V^2/(Re)^{1/5}$$

Two important relationships with which this dissertation is concerned are given here. The first is the relationship of density, velocity, length, and viscosity in fluid flow and the second is the shear expression which contained Re.

Wind Tunnel Investigations

Lapp (1962) conducted a wind tunnel study to determine the reduction of evaporation when a monolayer was applied to a water surface. The following statement concerning film detection was made in his thesis:

> Numerous attempts were made to utilize these indicator oils to detect the presence of a hexadecanol film. It was finally concluded that the method could not be applied to a laboratory project on the scale undertaken in this study. This finding was confirmed by Wolbeer of the Engineering division, Saskatchewan Research Council, who had similar experience during some of his evaporation studies.
>
> Camphor crystals as employed by Crow and Daniel (13) were found to work well to indicate the presence of a hexadecanol film. The crystals do not give any measure of film pressure.

It was stated that evaporation reduction in the laboratory was substantial at wind speeds up to 10 mph. A study of types and placement of wind shelters which may contribute to the maintenance of wind speeds below 10 mph was recommended. The tank used for these tests was 3 feet long.

Woodruff (1952) conducted a wind tunnel study to evaluate windbreaks used to reduce soil erosion. Several references were cited that gave the distance on the lee side of the windbreak that was effectively protected from erosion. DenUyl gave 12H, Flensberg 10H, Barth 12H, Anderson 6-15H, and Hopkins, Palmer and Chepil 15-30H. In this literature, H refers to the height of the wind break. Woodruff's value for a vertical flat plate was 13.0H, and 10.5H for a triangular shape.

Woodruff commented on the problem of an attempt to study multiple windbreaks in the wind tunnel. It was stated that for multiple windbreaks the interpretation of wind tunnel results to atmospheric conditions would be difficult. Solution to this problem was believed to require evaluation of artificial barriers under atmospheric conditions. This opinion expressed by Woodruff would lead one to expect difficulties in attempting to obtain meaningful data when more than two barriers were placed in a series in the wind tunnel. The report was summarized with a statement that flow patterns and effective velocity reductions for the vertical plate and triangular shape were nearly comparable; and, resistance to flow over a given object was independent of the magnitude of Reynolds Number for the velocities used.

The height of the objects used in Woodruff's study was 4 inches. This was considered to be the significant length in the Reynolds Number. It was stated that the change in Reynolds Number due to the change in the significant length of 4 inches, as used in the wind tunnel, to several feet for field conditions was not detrimental since the flow pattern over similar barriers approaches a constant for Reynolds Numbers of the magnitude considered.

Geiger (1965) showed isovel lines for two vertical reed screens 2.2 m high. One screen had a penetrability of 15 to 20 percent and the other had a penetrability of 45 to 55 percent. These showed effective protection for a distance of 10 to 12 times the height of the barrier. The above indicated that certain relationships that are developed in wind tunnel investigations can be transferred to field conditions with the expectation that similar results will be obtained.

Field Investigations

Field studies using hexadecanol to reduce evaporation from lakes were started in the early 1950's. Mansfield (1953) reported that the resistances of several monolayers and duplex films had been determined between 20°C and 60°C. The C_{16} and C_{18} aliphatic alcohols provided the least permeable layers. Under natural conditions during the summer of 1953, no significant evaporation reductions occurred. Strong winds destroyed the film. A 25 percent average reduction was obtained during the winter. It was stated that the use of surface films in the summer would not significantly reduce evaporation unless some method of restricting the absorption of radiation was provided.

Mansfield (1955) stated that his previous conclusion about significant reduction in evaporation was incorrect. If properly applied, it was predicted that average summer reductions in evaporation should reach 45 percent for inland Australia. This estimate was based on a surface pressure of 40 dynes/cm.

It was pointed out that surface pressure varied from 40 dynes/cm to practically zero with a 10 percent expansion of the film. A continous supply of alcohol was necessary to maintain high surface pressures. Field studies early in November of 1953 resulted in an average decrease in evaporation of 30 percent.

McArthur (1962) reported:

> With the steadily increasing demands for water, the need for conservation, particularly in tropical countries, is becoming more urgent. Over the last six years the use of monolayers of cetyl and stearyl alcohols to reduce evaporation losses from open water has proved to be both practical and safe.

An analysis was performed by Musgrave of the U. S. Public Health Service to determine the presence of hexadecanol in two public water supply systems. These results were reported by Middleton (1959). The report concluded that no hexadecanol was detected in the raw water from Lake Hefner (Oklahoma). The method of detection used was sufficiently sensitive to detect a concentration of 5 parts per billion.

United States field tests were first conducted in 1956 by the Bureau of Reclamation at Kid's Lake--an arm of Lake Hefner near Oklahoma City. This study was followed by more extensive studies on Lake Hefner, Oklahoma; Lake Mead, Arizona-Nevada; Sahuaro Lake, Arizona; Lake Cachuma, California; and several other locations.

Results of field studies have been encouraging for the most part. The Lake Hefner report (1958) showed a 9 percent reduction in evaporation during the period July 7 to October 2, 1958. Greater reductions--about 14 percent for the period October 1 to November 17, 1960--were obtained at Sahuaro Lake (1960). The above figures indicate a relatively small savings during the period October 1 to October 19, 1960. Similar results were obtained at Lake Cachuma (1962). Evaporation reduction ranged from 8 to 22 percent during a two month test period in the summer of 1961. These figures did not approach the 50 percent level which some previous studies had indicated might be obtainable. However, the reduced savings are what can be expected when the partial film coverage is taken into consideration.

Lack of complete coverage has been a major limiting factor in obtaining maximum reduction in evaporation. This was pointed out in the following statement by Florey, Newkirk, and Hansen (1962).

> From the first attempts to apply monolayers to reservoirs exposed to the influence of the wind, it was immediately apparent that wind conditions at any test site would be a governing factor in the longevity of the film and in the technique chosen for applying the film. The one exception to this statement would probably be in the work done by the Commonwealth Scientific and Industrial Research Organization in Australia in which field work has been done under almost ideal wind conditions, and the influence of wind upon the monolayer has been of little concern in their work. On the other hand early field investigations by the Bureau, the Geological Survey, Southwest Research Institute, Stanford University, and Oklahoma State University have indicated that a technique of continuous application of film-forming materials at a rate proportional to wind speed would probably utilize the materials most efficiently in reducing water evaporation.

Crow and Sattler (1958) reported fully compressed coverage on a 100 x 120 foot test pond was about 50 percent under a 3 mph wind and dropped to less than 2 percent under a 9 mph wind. The experience at Lake Hefner pointed out the problem of unidirectional wind throughout the test period. A large amount of chemical was required to maintain a film under such conditions. The Bureau of Reclamation reported (1959) that applications were impossible and impractical at speeds over 20 mph. Koberg (1961) stated:

> However, one conclusion is apparent and that is the wind factor. At Lake Hefner and Lake Cachuma the wind speeds averaged above 7 miles per hour during the film treatment period, and the savings in evaporation obtained were less than 10 percent. At Lake Sahuaro, the wind speed averaged below 5 miles per hour and a saving in evaporation of 14 percent was obtained. The results of these three tests indicate that a monolayer on a reservoir with low wind speeds will be more effective than with high wind speeds.

McArthur (1962) stated that one of the chief problems in treating a large water surface with a film was to maintain efficient coverage under varying conditions of wind. Price, Garstka, and Timblin (1959) commented on this problem at Lake Hefner. A very important and practical finding was recognition of the effect wind had on the behavior of the monolayer. The evaluation indicated wind was probably the most important factor influencing survival and effectiveness of the monolayer. Gusty characteristics of wind at Lake Hefner made it difficult to select a specific velocity above which application was impossible. However, the film was quickly swept across the reservoir or destroyed by wave action when average velocity exceeded 20 mph. Wind velocities up to 10 mph were beneficial in spreading the film.

Florey and Hansen (1961) reported on applying monolayer materials to Lake Sahuaro, Arizona. When attempting to apply film by use of a boat, it was impossible to maintain complete coverage if the wind exceeded 10 mph. Very little coverage could be maintained in winds above 15 mph.

The Lake Cachuma (1961) report pointed out that coverage of the water surface usually ranged from 20 percent to 60 percent. At times it reached 90 percent. This study was carried out in 1961 when wind velocity averaged more than 7 mph. Under lower wind velocities more complete coverage would have been expected. In this test the monolayer material was melted and sprayed out periodically by automatic dispensers which were activated by wind velocity and direction devices. If wind velocity ranged from 15 to 20 mph, there was little or no lateral spreading of the film. These patches terminated at the downwind shore or faded out about one half mile from the dispensers because turbulent wave action destroyed the film.

Crow (1963) reported that on small water surfaces--100 x 120 feet--19 mph was the highest wind speed for which it was possible to obtain any test data. Not only was it difficult to maintain coverage, but extremely heavy applications of chemical were needed. At the 19 mph wind, an application rate of 0.006 lbs of chemical per hour per foot of upwind shoreline were required as compared to 0.00026 lbs per hour with the wind velocity of 5 mph.

It is apparent from the preceding observations, expressed as a result of tests conducted at several locations, that some control of wind speeds would be of benefit to evaporation control using monolayers. The use of artificially constructed barriers is a possible solution. On large lakes where massive structures would be required and the presence of barriers would interfere with recreational facilities, the use of these barriers would be impractical. However, Crow (1958) reported there were over 870,000 farm ponds in Oklahoma, Texas, Missouri, Kansas, and Nebraska. These vary in surface area from 1 to 5 acres. The combined surface area of these small ponds contributes a considerable portion to the total evaporation losses. Artificial barriers constructed around or across these smaller reservoirs would not present the structural problems nor interfere as much with recreation.

Crow (1963) listed three possible approaches to the problem of maintaining a hexadecanol film on a water reservoir. These were: 1) continuous replenishment of the monolayer at the upwind shore, 2) reduce the wind speed near the water surface by windbreaks along the shore or floating on the surface, and 3) restrict the monloayer movement by confinement in small compartments. The approach mentioned in 2 and 3 above were recommended for use with small farm ponds. Barriers used in his studies were spaced 14.5 feet apart. This gave a gridwork made up of small reservoirs 14.5 feet square. When barriers 0.90 foot high were used and no film applied, evaporation was reduced 9 percent during the month of May. The reduction varied from 2.8 percent reduction at a velocity of 6 mph to a 15.2 percent reduction at about 14 mph. No reduction was experienced with a barrier height of 0.25 foot when tested in June.

An opposite result was obtained when a monolayer film was applied. With a 0.25 foot barrier height, evaporation reduction was about 29.9 percent under a 2 mph wind and only 6.7 percent at an 8 mph wind. The inability to maintain total film coverage at higher velocities was considered the cause of the decrease in film effectiveness.

It was stated that the L/H ratio of 16 yielded three times greater evaporation reduction than the L/H ratio of 58. L refers to the 14.5 foot distance between barriers and H is the height of the barrier. Evaporation suppression was not significantly greater with the barrier system but the amount of chemical required was less. An important conclusion of the above report was that a system of wind/film barriers held much promise for evaporation control on small reservoirs.

CHAPTER III

EXPERIMENTAL DESIGN

Theory

Flow of any fluid over a surface causes a drag on the surface. The fluid flowing over the surface in this investigation was air. A hexadecanol film spread over water was the surface on which the drag was exerted. The magnitude of the drag force and the ability of the film to resist this force were the factors which determined the extent of film coverage that could be maintained. Review of literature showed that the collapse pressure of the film, the density, viscosity and velocity of the air, and some length characteristics were logical factors to consider in this investigation.

A more difficult relationship to describe in theory was the influence of barriers placed in the air stream. These were observed as phenomena separate from the main study.

Dimensional Analysis

Many experimental investigations can be carried out more rapidly and provide more useful results if dimensional analysis is used. The Reynolds Number, which has been shown to apply to fluid flow problems, was developed on this basis. It seemed logical to proceed with dimensional analysis in this study. Using this approach, it was possible to describe the important factors involving the physical system by an equation made up of dimensionless parameters.

The method of dimensional analysis offers a means of simplifying experiments involving many variables and enables the researcher to obtain useful data with a minimum of experimental and computational effort. The method can be briefly summarized as follows: Quantities which are thought to have a measurable effect on the physical system are identified and analyzed dimensionally. These are then combined into dimensionless ratios known as pi terms which can be treated as variables. Omission of a pertinent quantity may result in the analysis being ineffective while consideration of an unimportant factor may reduce the usefulness of results and increase the required amount of experimentation. The number of pi terms required for a given set of quantities can usually be determined by the Buckingham Pi Theorem. This theorem states that the number of pi terms required to express a relationship among quantities in any physical system is equal to the number of quantities involved minus the number of dimensions in which these quantities may be measured. There is no unique set of pi terms for a given set of quantities. Other pi terms can be formed by division or multiplication of the terms within the set. The only restriction placed on the pi terms is that they be dimensionless and independent.

An equation expressing the relationship of the pi terms can be written as

$$\pi_1 = f(\pi_2, \pi_3, \ldots \ldots \ldots \ldots \ldots \ldots \ldots \pi_n) \qquad 3\text{-}1$$

which involves an unknown function. To formulate a prediction equation, the nature of the function must be established. This cannot be done by dimensional analysis alone, but it may be done from analysis of laboratory observations. Murphy (1950) suggested the following procedure for determining the type of function and for evaluating it. Observations are arranged so that all of the independent pi terms, except one, involved in the function remain constant. That one is varied to establish a relationship between it and the term being observed. The relationship established between the two terms is known as a component equation. This procedure is repeated for each of the other independent pi terms. Relationships between the quantity being observed and each of the other pi terms can be combined to give a general relationship. If the observations plot as a straight line on log-log paper, the component equations are of the form

$$\pi_1 = C\pi_n^a \qquad 3\text{-}2$$

Pi terms will combine by multiplication and the general prediction equation will have the form

$$\pi_1 = C_1\pi_2^{C2}\pi_3^{C3} \ldots\ldots\ldots\ldots \pi_n^{Cn} \qquad 3\text{-}3$$

If observations plot as straight lines on arithmetic paper, the pi terms will combine by addition and will have the form

$$\pi_1 = C_1 f(\pi_2) + C_2 f(\pi_3) + \ldots\ldots\ldots + C_s f(\pi_s) + C \qquad 3\text{-}4$$

Film Coverage with Unobstructed Air Flow

The first tests were conducted with a minimum of interference to the air flow. Quantities considered pertinent to this part of the research are given in Table I.

Selection of the pi terms depends on some knowledge of the system with which one works. The first pi term was developed and written as

$$\pi_1 = (XF \times \rho \times V \times Ne)/\mu \qquad 3\text{-}5$$

The above term was a form of Reynolds Number using hexadecanol film coverage (XF) as the significant length term.

The second pi term, peculiar to the system studied as it contained the collapse pressure of the hexadecanol film, was

$$\pi_2 = (\mu \times V)/Pc \quad 3\text{-}6$$

Satisfaction of the Buckingham Pi Theorem was accomplished by writing π_3--a form of Froude Number--as

$$\pi_3 = V/\sqrt{g \times XF} \quad 3\text{-}7$$

Other pi terms could have been written but these three seemed to associate the pertinent quantities in meaningful groups.

π_1 was considered the dependent variable with π_2 and π_3 being independent. The general equation for this group was

$$\pi_1 = f(\pi_2, \pi_3) \quad 3\text{-}8$$

or

$$(XF \times \rho \times V \times Ne)/\mu = f((\mu \times V)Pc, V/\sqrt{g \times XF}) \quad 3\text{-}9$$

TABLE I

PERTINENT QUANTITIES FOR UNOBSTRUCTED AIR FLOW

No.	Symbol	Quantity	Dimension
1	Pc	Film collapse pressure	FL^{-1}
2	ρ	Air density	ML^{-3}
3	μ	Air viscosity	FTL^{-2}
4	V	Air velocity	LT^{-1}
5	XF	Film length	L
6	Ne	Newton's second law coefficient	$FM^{-1}L^{-1}T^{-2}$
7	g	Acceleration due to gravity	LT^{-2}

Dimensions in Table I were defined as follows:

F = Force M = Mass

L = Length T = Time

Number of pi terms = 7 - 4 = 3

Barrier Influence

Objective 2 of the investigation was to determine the influence of several barrier configurations. The list of pertinent quantities that were thought to apply in this situation are given in Table II.

TABLE II

PERTINENT QUANTITIES FOR OBSTRUCTED AIR FLOW

No.	Symbol	Quantity	Dimension
1	Pc	Film collapse pressure	FL^{-1}
2	ρ	Air density	ML^{-3}
3	μ	Air viscosity	FTL^{-2}
4	V	Air velocity	LT^{-1}
5	XF	Film length	L
6	Ne	Newton's second law coefficient	$FM^{-1}L^{-1}T^{-2}$
7	H	Barrier height	L
8	XW	Spacing of barriers	L
9	α	Angle of barrier with surface	--
10	p	Percent perforated area	--
11	n	Number of bays of water	--
12	PH	Perforation height	L
13	W	Width of a horizontal barrier	L

Dimensions in Table II were defined as follows:

F = Force M = Mass

L = Length T = Time

Number of pi terms = 13 - 4 = 9

π_1 of this system was the same as for the first objective and was written

$$\pi_1 = (XF \times \rho \times V \times Ne)/\mu \qquad 3\text{-}10$$

Similar to the first system, π_2 was defined as

$$\pi_2 = (\mu \times V)/Pc \qquad 3\text{-}11$$

A form of Reynolds Number was written as

$$\pi_3 = (Ne \times \rho \times H \times V)/\mu \qquad 3\text{-}12$$

Additional pi terms applicable to this system were

$$\pi_4 = H/XW \qquad 3\text{-}13$$

$$\pi_5 = W/XW \qquad 3\text{-}14$$

$$\pi_6 = PH/H \qquad 3\text{-}15$$

$$\pi_7 = \alpha \qquad 3\text{-}16$$

$$\pi_8 = p \qquad 3\text{-}17$$

$$\pi_9 = n \qquad 3\text{-}18$$

A generalized equation for this system was

$$\pi_1 = f(\pi_2, \pi_3, \pi_4, \pi_5, \pi_6, \pi_7, \pi_8, \pi_9) \qquad 3\text{-}19$$

or

$$(XF \times \rho \times V \times Ne)/\mu = f((Ne \times \rho \times H \times V)/\mu\ ,\ (\mu \times V)Pc,\ H/XW,\ W/XW,\ PH/H, \alpha\ ,\ p,\ n) \qquad 3\text{-}20$$

Discussion of Pertinent Quantities

Results obtained from any experimental investigation depend on the selection of quantities pertinent to the project. Limitations imposed by available facilities restrict the number of pertinent quantities that can be measured and studied.

The pertinent quantities listed in Tables I and II were considered either measurable or sufficient data were available from the literature to enable making an adequate estimate of the quantity.

Collapse pressure (Pc) of the film had been determined by physical chemists at two temperatures near the lower and middle regions needed for this study. Preliminary investigations carried out in the wind tunnel showed that the change in collapse pressure with temperature was nearly a linear relationship and the error introduced by making this assumption would be small. Collapse pressure values were calculated on this basis.

Air density (ρ) and viscosity (μ) were known to influence fluid flow problems. Values for these quantities were calculated from data taken for temperature and barometric pressure. Velocity was measurable directly by use of a thermo-anemometer.

Newton's second law coefficient had a fixed value. The value of g--acceleration due to gravity--was considered a constant for all locations where results of this study might be applied. Height of the barrier (H), width of horizontal barriers (W), spacing of barriers (XW), angle of barrier with the surface (α), perforation height (PH), percent perforated area (P), and number of bays of water (n) were all quantities that could be measured directly.

The film length (XF) was measurable but not as accurately as other pertinent quantities. Difficulty in locating the film edge and the inaccessibility of the water surface made this quantity more subject to error.

Discussion of Dimensionless Ratios

Numerous dimensionless ratios can be formed from the pertinent quantities selected for this investigation. Random selection may not result in meaningful data being taken. A careful selection of pi terms provides the investigator with data that is more likely to give a prediction equation describing the functions of the system.

$(XF \times \rho \times V \times Ne)/\mu$ was the first pi term selected. This term was suggested by the combination of shear per unit area and length of film on which this shear acted to develop the pressure necessary to collapse the film. The shear was dependent on the quantities ρ, V, and Ne. π_1 was the dependent variable. It contained the term XF which was to be predicted for future use.

Three π_1 terms are used in the analysis. π_1 without a superscript was used with film coverage measurements made at the downwind end of the reservoir. π_1' was the selected designation when film coverage was measured in the lee of the barrier. π_1'' indicated total film coverage--downwind film coverage plus film coverage in the lee of a barrier.

$(Ne \times \rho \times H \times V)/\mu$ was a form of Reynolds Number using the height of the barriers as the significant length term.

$V/\sqrt{g \times XF}$ was a form of the Froude Number and accounted for effects due to wave action.

$(\mu \times V)/Pc$ related the collapse pressure to the viscosity and velocity of the fluid developing the collapse pressure. Other pi terms that might have been used did not relate directly to the system.

H/XW was a ratio relating the height of the barrier to the spacing between barriers or the distance from the barrier to the opposite end of the reservoir.

W/XW was a ratio selected to relate the width of a low, flat barrier to the spacing between the barriers.

Ph/H was a ratio of the distance of a perforated area from the base of the barrier to the total height of the barrier. This term was selected to determine if positioning of open areas would influence the film coverage.

α was a dimensionless term used to investigate the influence on film coverage when barriers were sloping rather than vertical.

p was a dimensionless term describing the percent of the barrier area that was perforated.

n was a dimensionless term used to evaluate effects caused by a series of water surfaces enclosed or protected by barriers.

Proper evaluation of the component equations required that all pi terms, except the dependent one and the independent term influencing the dependent term, be kept constant during a series of tests. This was not possible in this investigation because there was no way to control the air temperature and barometric pressure. Viscosity and density of the air were influenced by these two uncontrollable factors.

Multivariable Analysis

The inability to control some of the pertinent quantities in this study, required the consideration of an alternate approach to the problem. Taking data at various levels of air velocity, air temperature, barometric pressure and film temperature would provide data whereby a multivariable regression analysis might be made. Individual pi terms could be considered variables or each pertinent quantity could be evaluated as a variable. The first of these groupings would combine those quantities known to be related in fluid flow problems and might give more simple expression. Use of the individual pertinent quantities would reveal individual effects but result in a more complicated prediction equation. Graphical portrayal of results would be easier with simple equations.

CHAPTER IV

EXPERIMENTAL FACILITIES

Wind Tunnel

The major equipment component available for conducting the experimental investigation was a low velocity wind tunnel (Figure 1). Wind velocities up to 40 mph were available if needed. Length of the test section was 50 feet. Width and height were 4 feet. Air was drawn through the wind tunnel by use of a 16 blade, variable pitch fan. The pitch was set so wind speeds from 4 to 27 mph were obtained by adjusting the variable speed drive on the installation. The entrance design of the wind tunnel provided a relatively uniform air velocity across the entire entrance area of the test section.

Air Flow Modification

The air velocity profile under natural conditions is characterized by low velocity near the water surface and increasing velocity as the elevation above the surface increases. Theoretically this increase continues indefinitely. Practically, air velocity measurements can be accepted for describing velocity components when the change in velocity per unit of elevation is some small percentage of the total velocity. The percentage used depends on the precision of the measuring instrument.

A uniform flow pattern was assumed at the entrance of the 50 foot test section. Using the equation $\delta = 0.376(\nu/V)^{1/5}\ x^{4/5}$, the boundary

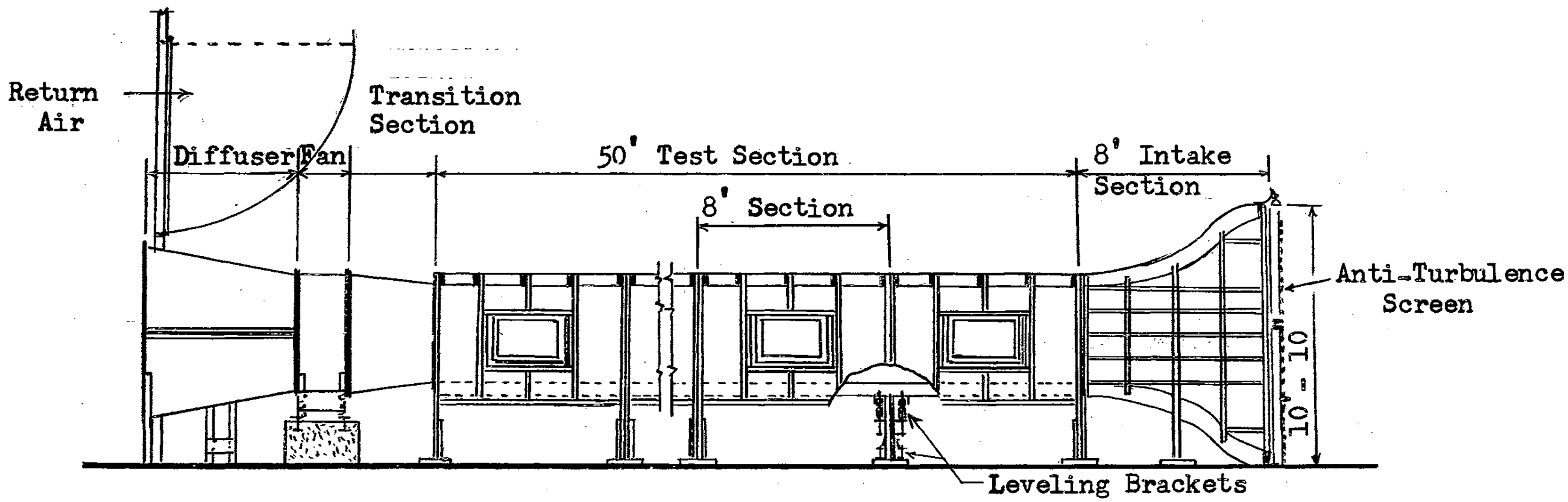

Figure 1. Wind tunnel used in this investigation. Cross-sectional area is 4 feet by 4 feet. Total length of the test section is 50 feet. Air velocities up to about 40 mph are obtainable. Twenty-six feet of the original top was replaced with sections having a 1 foot wide strip of plexiglass so observations could be made from above.

layer thickness developed at the beginning of the reservoir ranged from 0.48 foot to 0.38 foot at an air temperature of 80°F and velocities ranging from 4 fps to 25 fps.[1] The above boundary layer characteristics were not considered representative of field conditions. Modification of the air profile was accomplished by inserting a combination of wires and rods so that air velocity measurements taken in the lower half of the wind tunnel met the selected conditions. The wind tunnel velocity profile was developed with the restriction that variation was less than 2 percent in measurements taken at points 2 inches apart in the lower half of the test section. Figure 2 shows the device used to modify the air profile.

Water Reservoir

The size of water reservoir (Figure 3) selected for this investigation was 6 inches deep, 32 inches wide, and 24 feet long. A 6 inch depth provided space to install a heat exchanger and insured negligible influence on the water surface due to the proximity of piping or a solid surface. Two factors influenced the width of the reservoir: 1) the widest possible reservoir that could fit into the wind tunnel without edge effects causing interference over the water surface, and 2) standard sizes of sheet metal. A 36 inch reservoir would not have been too wide but the 32 inch width was the largest size that could be constructed from 48 inch wide sheet metal. The reservoir length was limited to 24 feet. Length was governed by the length of the wind tunnel. Space was required at each end of the reservoir to enter the wind tunnel to

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[1] ν = kinematic viscosity (μ/ρ).

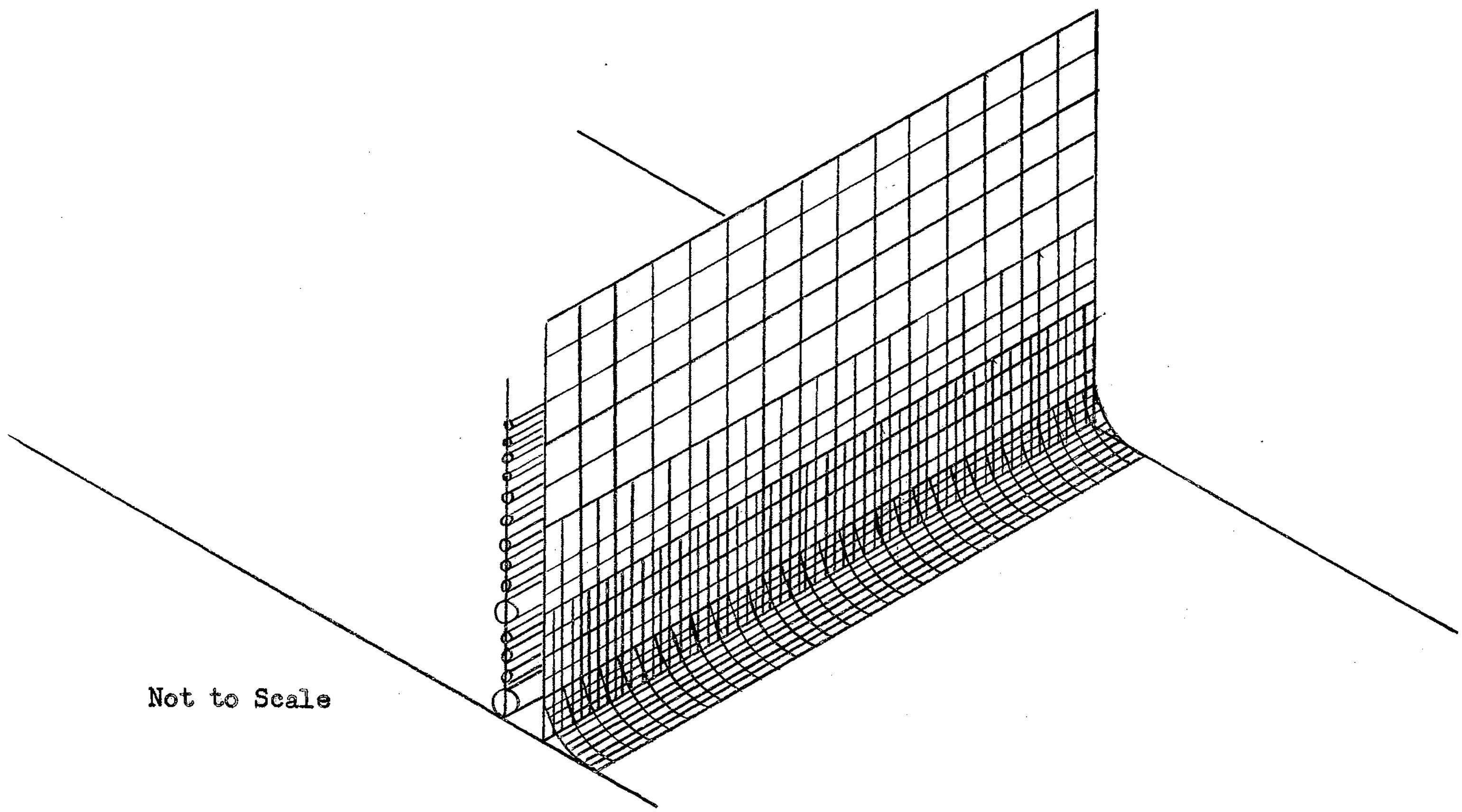


Figure 2. Device used to modify air velocity profile. One-half inch mesh hardware cloth was used as the foundation. The lower portion was interlaced with wire to provide a mass flow rate approximating the desired velocities. A curved segment of hardware cloth was placed in front of the upright section to improve flow in the lower three to four inches of the wind tunnel. Immediately downwind from the hardware cloth, an arrangement of various diameter rods was placed. The size and spacing of these rods were varied to obtain the final profile to be used.

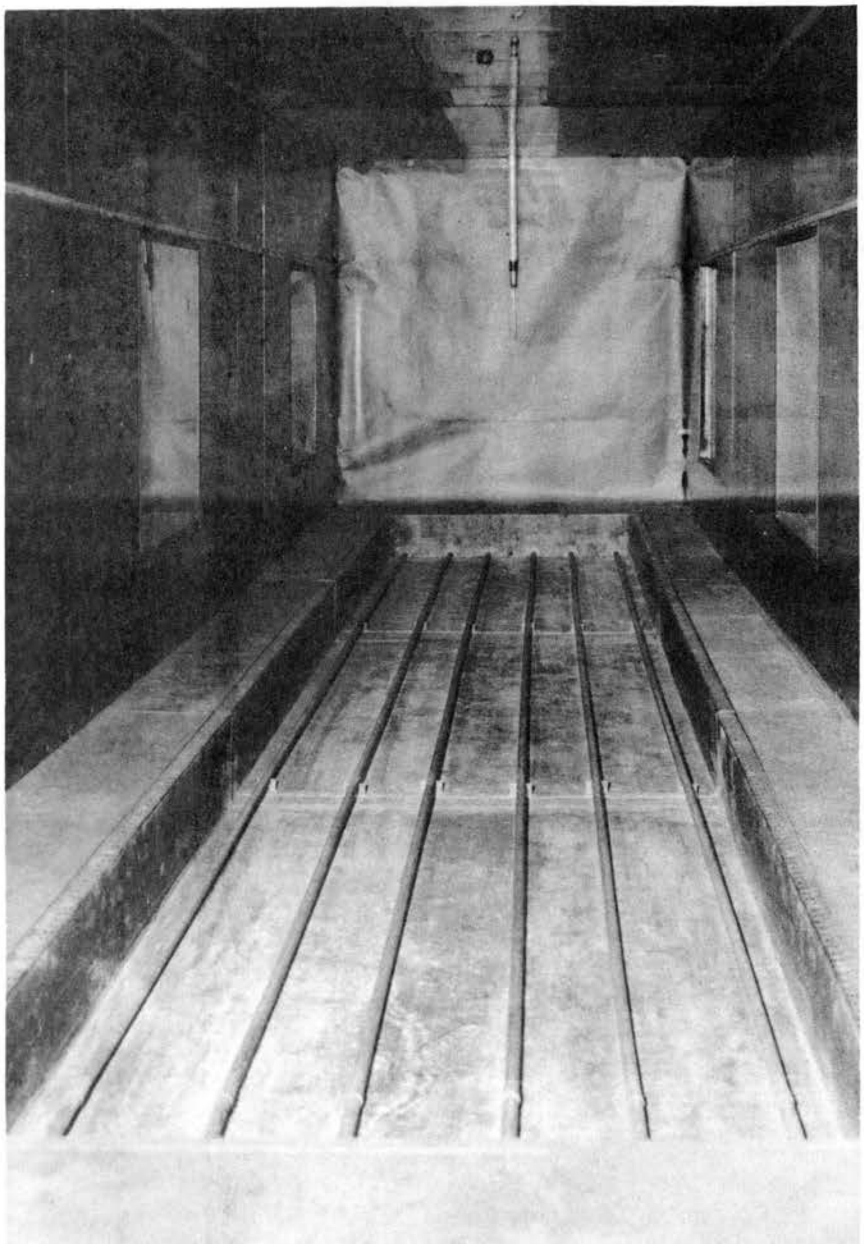


Figure 3. Water reservoir viewed from the downwind end of the wind tunnel. The reservoir is 6 inches deep, 32 inches wide, and 24 feet long. Six 1/2 inch diameter copper pipes--used for heating or cooling the water--make up the heat exchanger. The upper edge of the reservoir is flush with the floor of the wind tunnel.

install barriers and instrumentation. A device to modify the air flow pattern was placed upwind from the reservoir. Sufficient distance was required so eddy effects caused by the wires and bars would be smoothed out before air reached the instrumentation and the reservoir. Previous studies on use of bars and wires to modify the air profile had shown that a distance 24 times the diameter of the rods was adequate to permit eddy currents caused by the rods to become negligible. The device used in this study was placed 3 feet from the upwind end of the reservoir to insure adequate damping. According to earlier studies, 1 foot was sufficient.

Heat Exchanger

Temperature of the water was controlled during the experiments. This was accomplished by installing a heat exchanger (Figure 3) in the bottom of the reservoir. Six copper pipes of 1/2 inch diameter were placed the entire length of the reservoir. These extended 6 inches outside on each end and were connected by a manifold pipe. Design was based on a transfer of 30,000 BTU per hour which matched the heating capacity of the gas hot water heater used to supply hot water. Later, a milk can cooler was used to provide cold water to the heat exchanger.

Air Velocity Measurements

Air velocity measurements were made quickly throughout the test series. The rpm of the fan was not a repeatable setting that could be used to obtain the same velocities in test replications. Several attempts were made to adapt existing air flow equipment but none were successful. The pitot-static tube was not easily moved to all areas of the wind tunnel and did not give velocity readings directly. Direct readings were not obtainable with the existing hot wire anemometer.

An Alnor thermo-anemometer was used to make the air velocity determinations. It was direct reading and gave the air speed in feet per minute (fpm). Two scales of velocity were available ranging from 10 fpm to 2000 fpm. All work for this group of tests was carried out using the high range. The instrument probe contained two thermocouples through which a known current passed. One thermocouple was exposed to the air stream and showed the response due to the cooling effect of the passing air. Temperature compensation was accomplished by use of the second thermocouple which was protected from the air flow. A mercury battery supplied power for the anemometer. Adjustment for voltage drop as the battery became weak was provided by means of an internal calibration circuit which enabled the operator to check the instrument at regular intervals. This was generally done every hour or whenever any question arose concerning the magnitude of a velocity.

Accurate location of the probe was assured by use of brackets mounted on top of the wind tunnel (Figure 4). The vertical structural steel angles were set plumb. A pointed bolt was installed in each structural steel angle so that when holes drilled in the probe extension fitted over the bolt, the hot wire was the correct distance from the floor and oriented perpendicular to the air flow. Figure 7 shows the probe construction and the read out instrument.

Velocity profile measurements were taken at three positions lengthwise of the reservoir. The first position was 6 inches upwind from the edge of the reservoir. At midpoint of the reservoir, a second set of measurements was taken. A third set of measurements was taken 6 inches upwind from the downwind end of the reservoir.

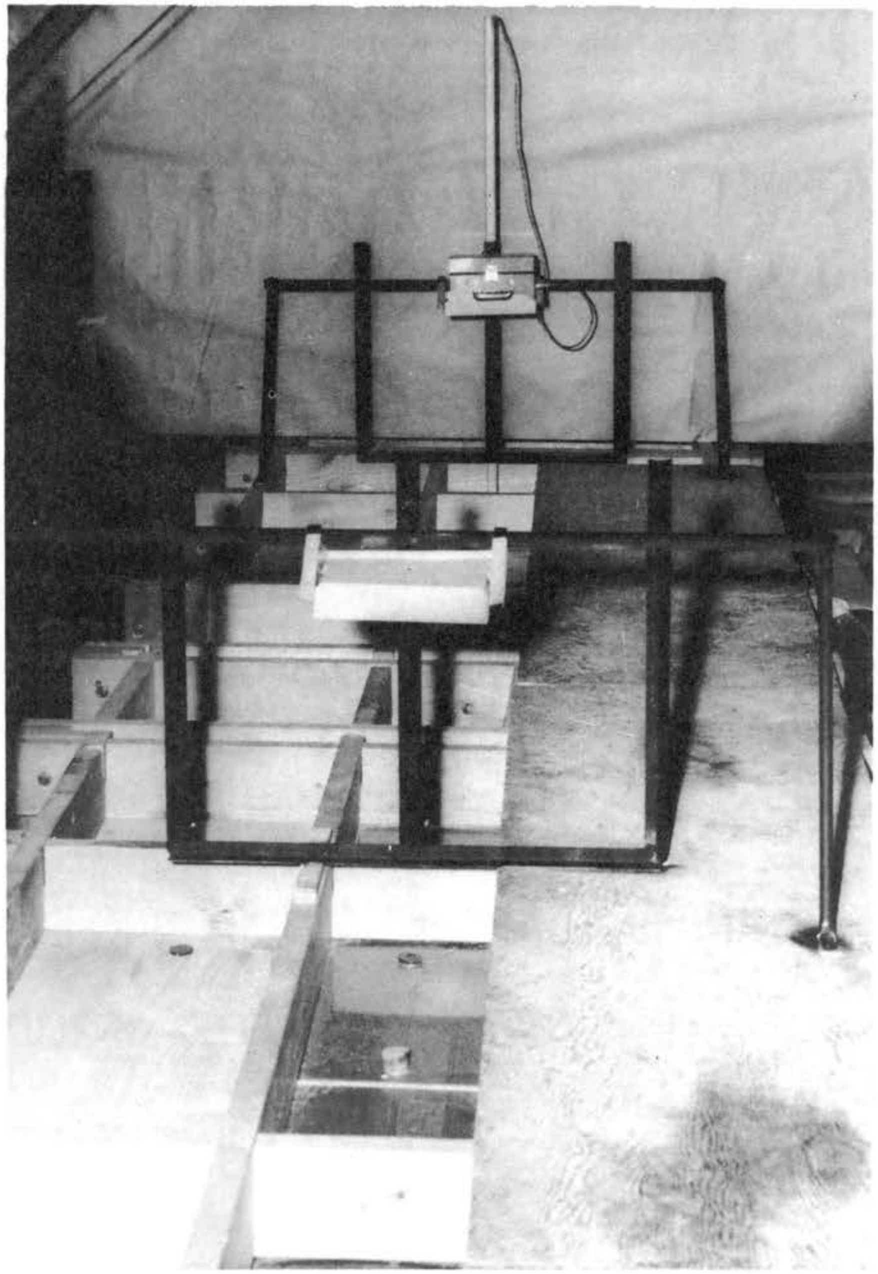


Figure 4. Brackets mounted on top of the wind tunnel. The three vertical segments provide a rigid brace for the probe and hold it plumb. The center location is on the center line of the wind tunnel. Side locations are 10 inches from the walls of the wind tunnel.

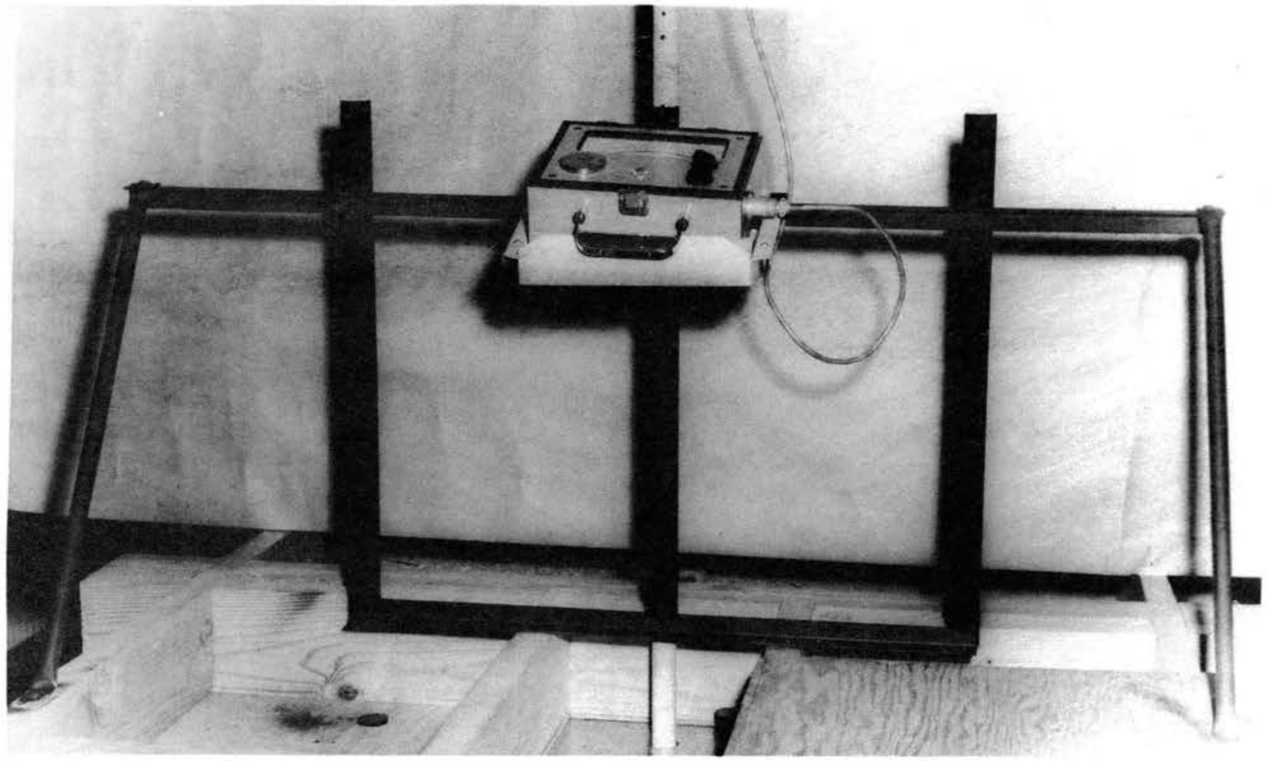


Figure 5. Thermo-anemometer mounted in the wind tunnel. Taken atop the wind tunnel, it shows the read out instrument resting on a foam rubber cushion inside a sheet metal support. The two holes in the probe, visible near the top of the picture, are used to position the probe vertically and insure correct orientation in the air stream.

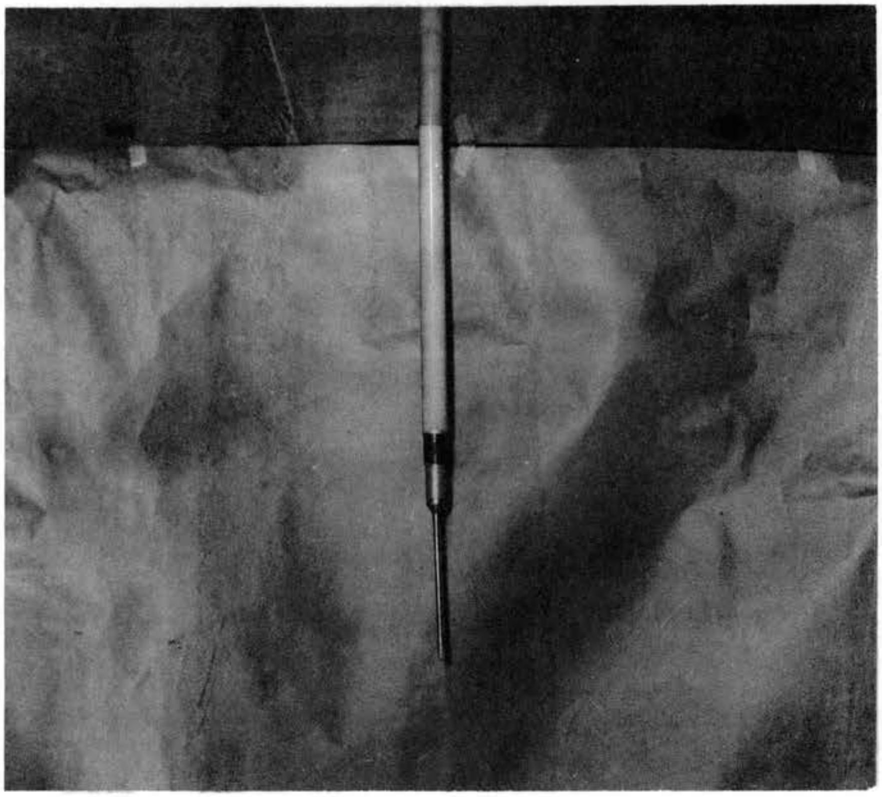


Figure 6. Thermo-anemometer probe mounted in the wind tunnel. The sensing element is located on the center line and 24 inches from the floor. With this unit, it was possible to take air velocity measurements at selected points between 1 inch and 24 inches from the floor of the wind tunnel.

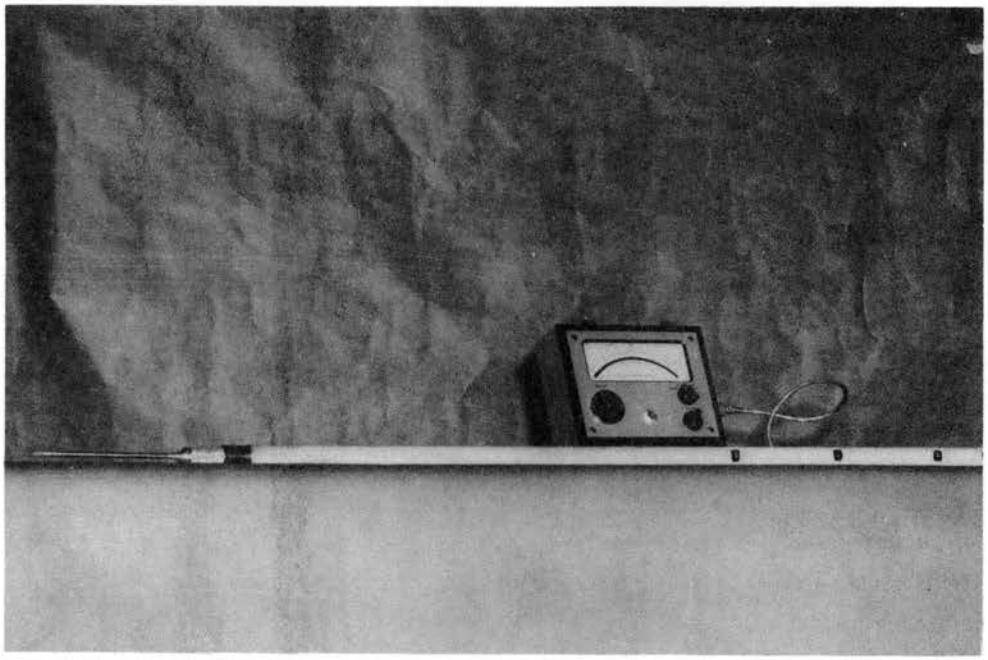


Figure 7. Thermo-anemometer and modified probe. A 1 foot probe, at the extreme left, was supplied with the instrument. The dark band is a retaining sleeve to hold the probe handle against a ring soldered inside the steel extension tube. Dark spots on the probe extension are distance markers to insure proper vertical positioning when velocity measurements are being made.

Three lateral positions were used at each of the three longitudinal points. One set was taken 10 inches from the left wall, one set on the center line, and the third set 10 inches from the right wall of the wind tunnel. The right and left positions were 2 inches from the sides of the reservoir. The above orientation was obtained when the observer looked from the entrance section toward the fan.

Miscellaneous Equipment

A thermistor thermometer (Figure 8) was used to measure water temperature. Scale graduations were in degrees and could be estimated to the nearest 0.2 degree. The temperature range was from 50°F to 100°F. Wet and dry bulb air temperature measurements were made with a sling psychrometer. Barometric pressure was measured with a mercury barometer.

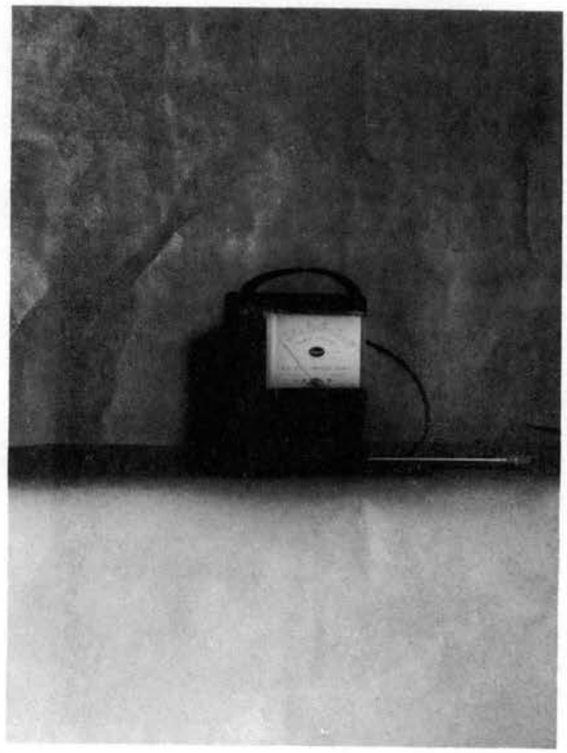


Figure 8. Thermistor thermometer used to determine water temperture. Full scale ranged from 50°F to 100°F. It was possible to estimate reading to the nearest 0.2°F.

CHAPTER V

EXPERIMENTAL PROCEDURE

Introduction

Rate and method of applying the hexadecanol film were two factors considered early in the study. Measurements for determination of the velocity profile were made second. Extent of the work required depended on the need for investigating each set of conditions under several velocity profiles. A comparison of effects due to change in velocity profile was made. Tests were conducted to determine the effect of air velocity and film temperature. Barriers of 2, 4, and 6 inch heights were used to determine their influence on film coverage. Effects of sloping barriers and lightly perforated barriers were investigated.

Hexadecanol Film

An excess of hexadecanol was used to insure complete coverage of the water surface. Hexadecanol dissolved in methanol was applied by use of a hypodermic syringe. An amount somewhat less than necessary to give complete coverage was put on at several locations over the surface of the water. This film was allowed to spread for a few minutes. Small additional amounts of hexadecanol were then added and allowed to spread. Finally, drops of hexadecanol did not spread but remained as a lens where placed. This check was made near both ends and the center of the reservoir. At intervals throughout a sequence of tests, additional hexadecanol was applied to insure an adequate amount of film on the water surface.

After a fully compressed film was applied, about 1/4 teaspoon of micronized aluminum was spread over the surface. Spreading was accomplished by placing the aluminum in a 200 mesh sieve, holding the sieve about 12 inches above the film surface and lightly tapping the sieve. Aluminum particles drifted through the air and settled gently on the hexadecanol film surface.

Typical Test Procedure

In the majority of the tests where film coverage was measured, the same general procedure was followed. After establishing a fully compressed monolayer and applying aluminum powder, the fan was started. Air velocity was increased until the film parted from the upwind edge of the reservoir or, in the case of barriers, parted at some point downwind from the barrier. The edge of the film was observed until there was no noticeable additional recession of the film edge. Approximate location of the film edge was made by observing movement of the aluminum particles. Exact location was determined by the line made visible through the interference pattern developed by light reflecting from the water surface and the hexadecanol film surface.

Velocity Profile Determination

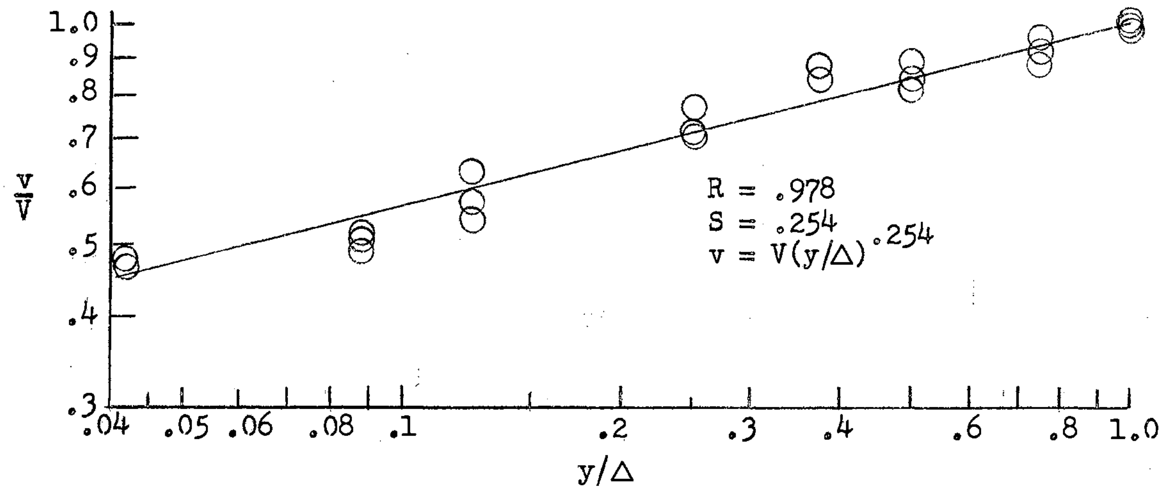
The air velocity at different elevations above the water surface was measured so that it would be possible to make a comparison, if necessary, with similar air flow patterns in nature. Profile data was taken when water covered with a hexadecanol film filled the reservoir. For the wind tunnel installation, velocity measurements were taken at 1, 2, 3, 6, 9, 12, 18, and 24 inches above the floor of the wind tunnel. Data taken at the upwind end of the reservoir are given in Appendix A-1 and A-2. In the equation $v = V(y/\Delta)^x$, y is the distance from the water surface up to the point at which the velocity (v) was measured. V was considered the free stream velocity, Δ was the distance from the floor to the point at which V is measured, and x an exponent needed to describe the velocity profile. In this case, Δ was 24 inches. Typical plots of v/V versus y/Δ are given in Figure 9. The same definition applies to all uses of this equation.

The change in profile throughout the length of the reservoir was obtained by taking velocity measurements 6 inches upwind from the reservoir, at the 12 foot point of the reservoir, and 6 inches upwind from the downwind end of the reservoir. Appendix A-3 contains data taken on the centerline of the wind tunnel at the upwind, center, and downwind positions.

Velocity Profile Comparison

The effect of different velocity profiles was of interest because it would have a bearing on the scope of the experimental work to be carried out. Evaluation of this relationship was the first to be undertaken.

Using a velocity profile of $v = V(y/\Delta)^{.17}$, a series of tests was conducted. The measured quantity was the extent of film coverage. Water temperature was the only factor that was maintained constant throughout the test. Temperature selected for these tests was 90°F. Ambient air temperature and barometric pressure were used and as a result, air density and viscosity fluctuated accordingly.



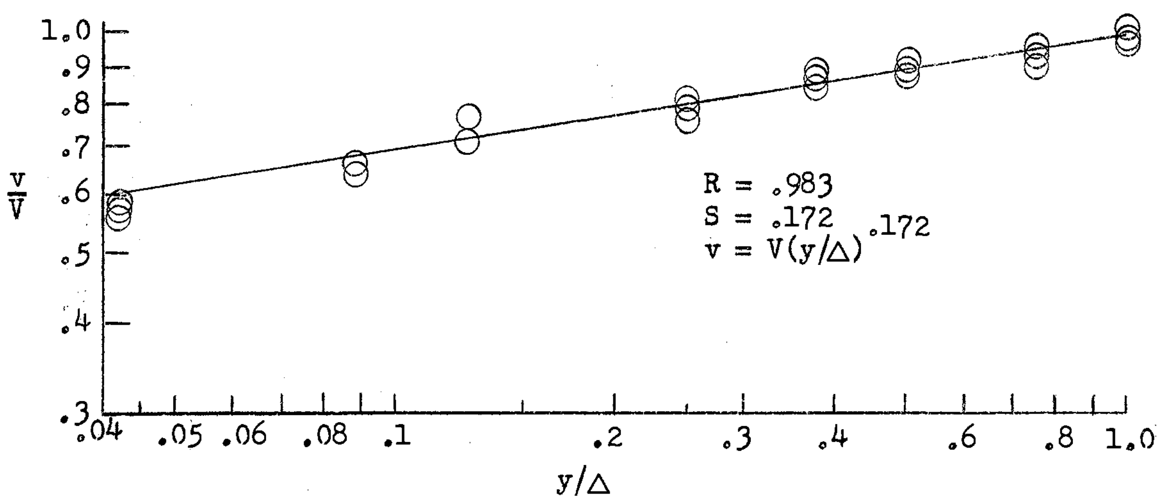


Figure 9. Typical plots of v/V versus y/Δ .

Air velocity was controllable and was the major quantity changed. Five different free stream velocities--from 490 to 1110 fpm--were used. The test was repeated three times. A second set of tests was carried out with a velocity profile identified as $v = V(y/\Delta)^{.25}$. In this case, seven different velocities--from 510 to 1110 fpm--were used. Three repetitions were carried out. Data from these tests are given in Appendix A-4 and A-5.

Barrier Influence

Influence of barrier heights was investigated by using sheet metal barriers having a vertical projection of 2, 4, and 6 inches (Figure 10). Water temperature was maintained at 90°F. Air velocities used in these tests ranged from 605 fpm to 865 fpm. Measurements were made of film coverage in the lee of the barrier and at the downwind end of the reservoir. Two separate groups of tests were conducted--one with a single barrier at the upwind end of the reservoir and one with a barrier at each end of the reservoir. Data from these tests are tabulated in Appendix A-6. Figure 11 shows a 6 inch barrier installed at the upwind end of the water reservoir.

Effect of sloping barriers was studied by using barriers having a 6 inch vertical projection. The angle of slope was measured from the horizontal surface. Angles of 30, 60, and 90 degrees (Figure 12) were used. A 90°F water temperature was maintained throughout these tests. Free stream air velocities from 610 fpm to 865 fpm were used. Appendix A-7 lists these data.

Preliminary studies indicated there might be a significant effect on film coverage due to use of a horizontal barrier (Figure 13). Horizontal barriers were constructed of sheet metal and installed (Figure 14) so a

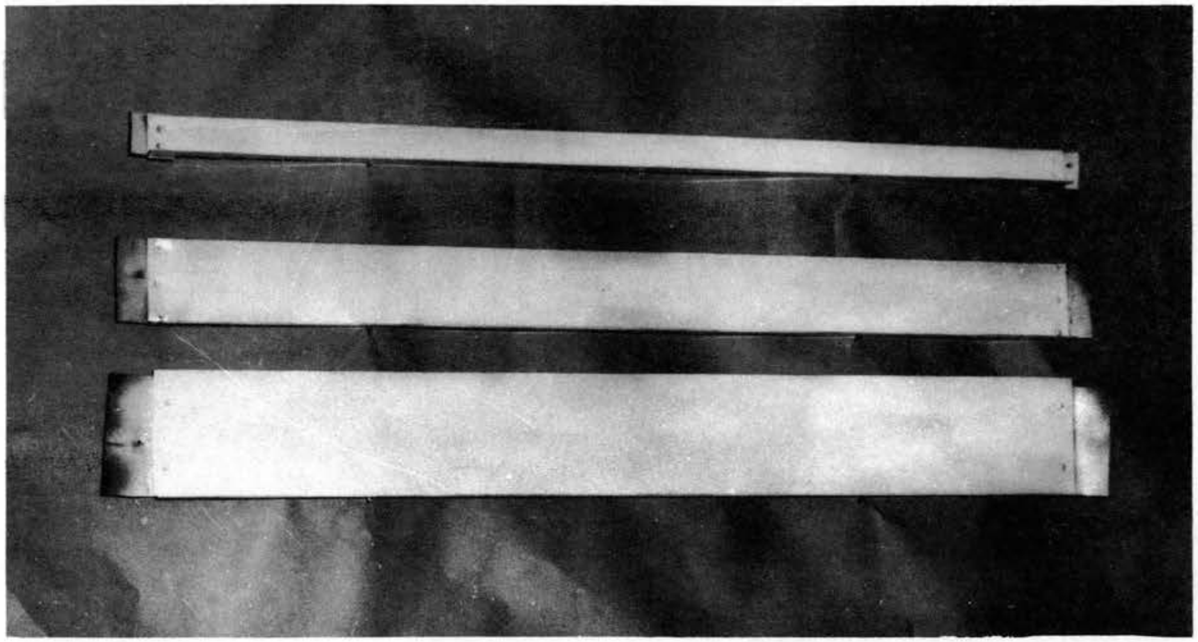


Figure 10. Vertical barriers--2, 4, and 6 inches high. The rubber gaskets at each end insured an air tight seal at the ends of the barrier.

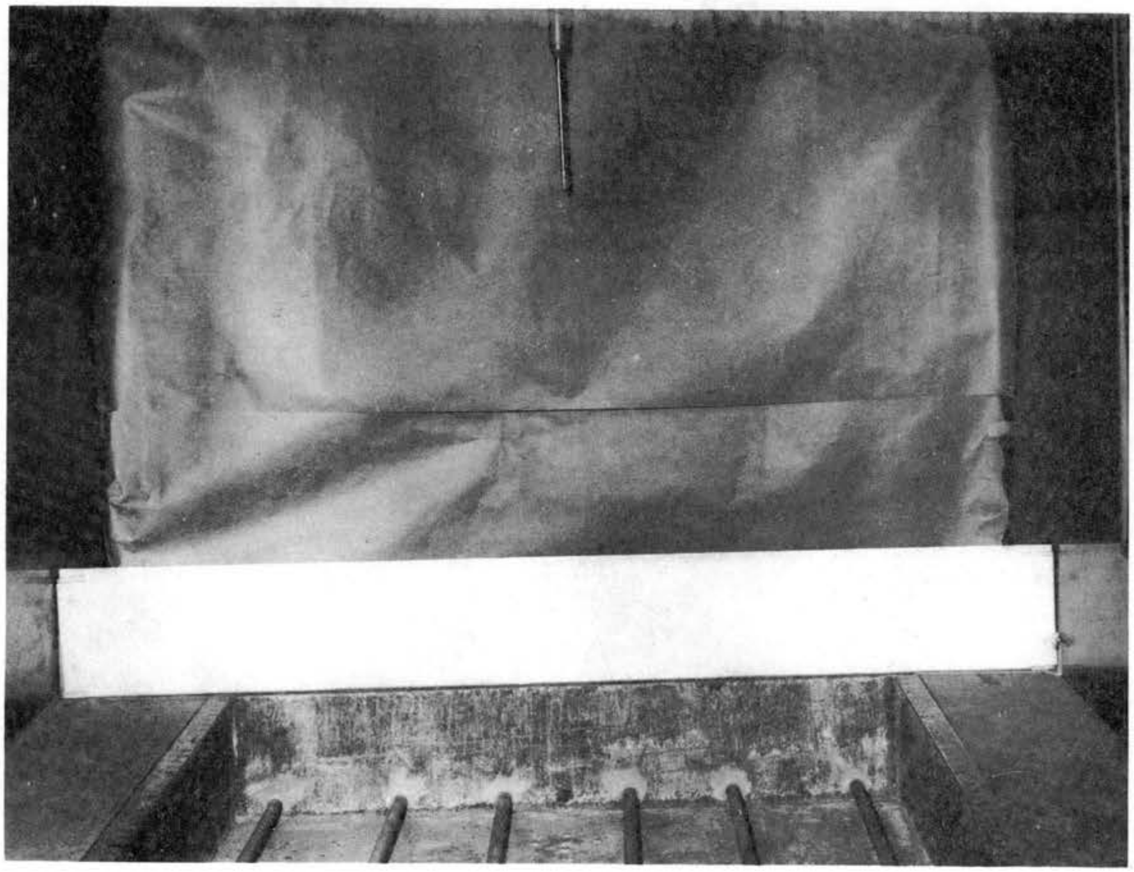


Figure 11. Vertical barrier installed at the upwind end of the reservoir. Masking tape was used to anchor the barrier in position. This insured an air tight seal between the ends of the barrier and the wall of the wind tunnel, and between the bottom of the barrier and the floor of the wind tunnel.

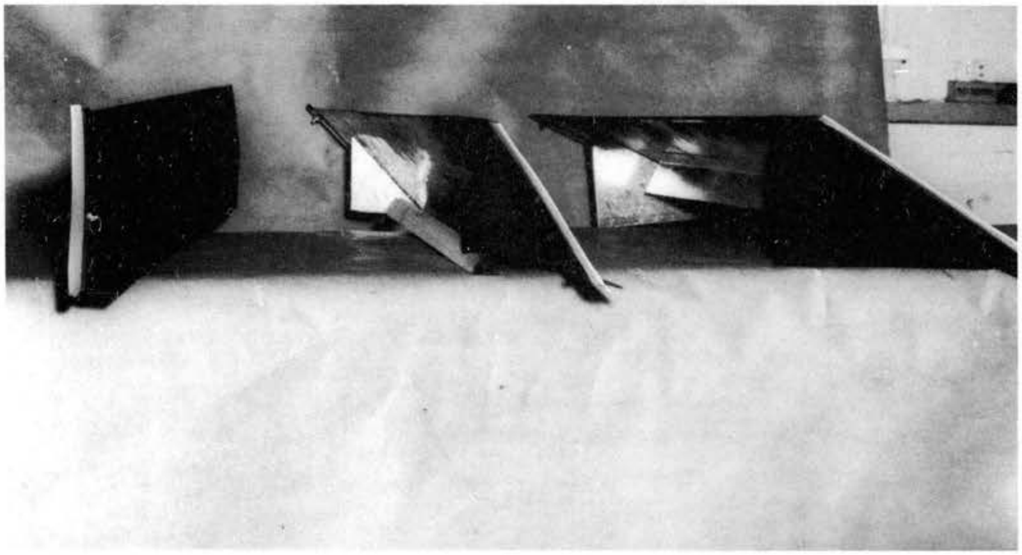


Figure 12. Sloping barriers. Reading from left to right--90°, 60°, and 30°. The vertical projection in each case was 6 inches. Leading edges of the 60° and 30° barriers were placed directly above the upwind end of the reservoir.

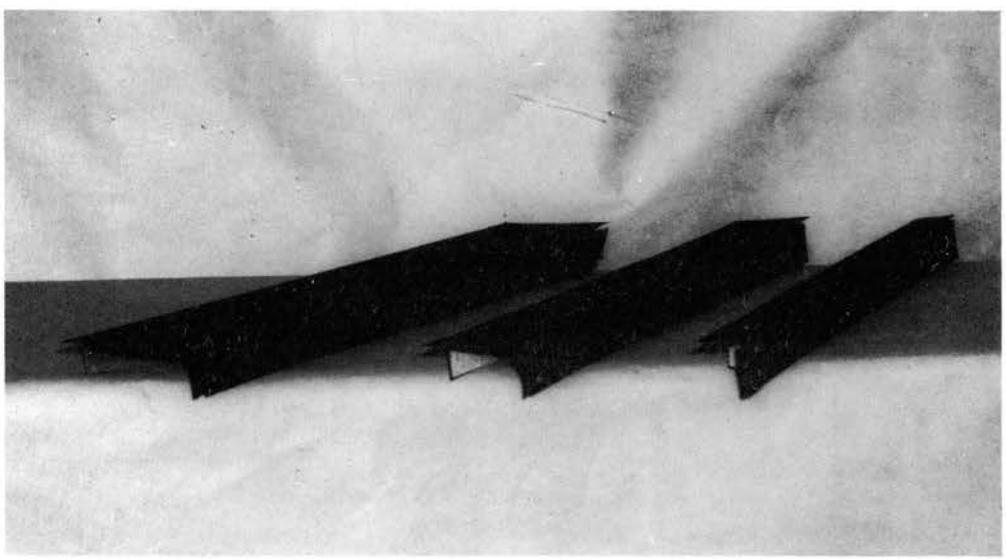


Figure 13. Horizontal barriers. Reading from left to right--6, 4, and 2 inch widths.

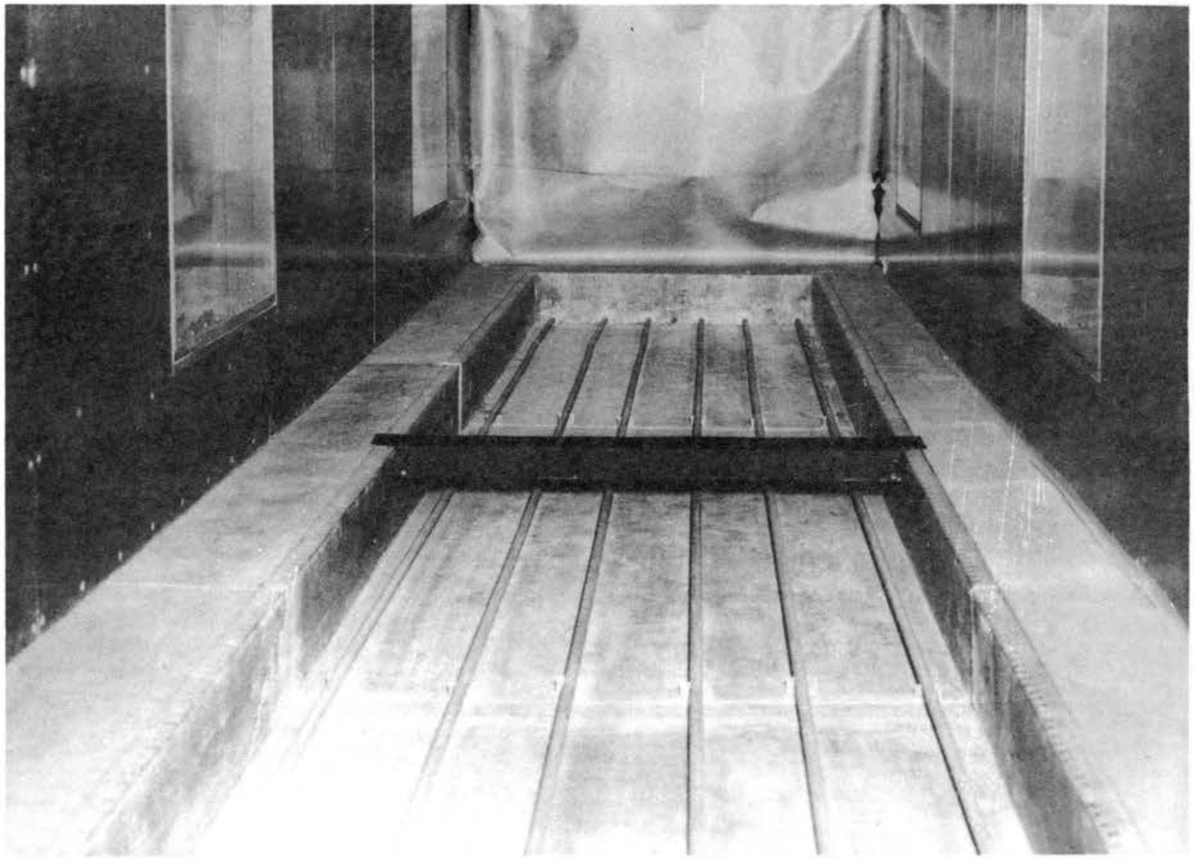
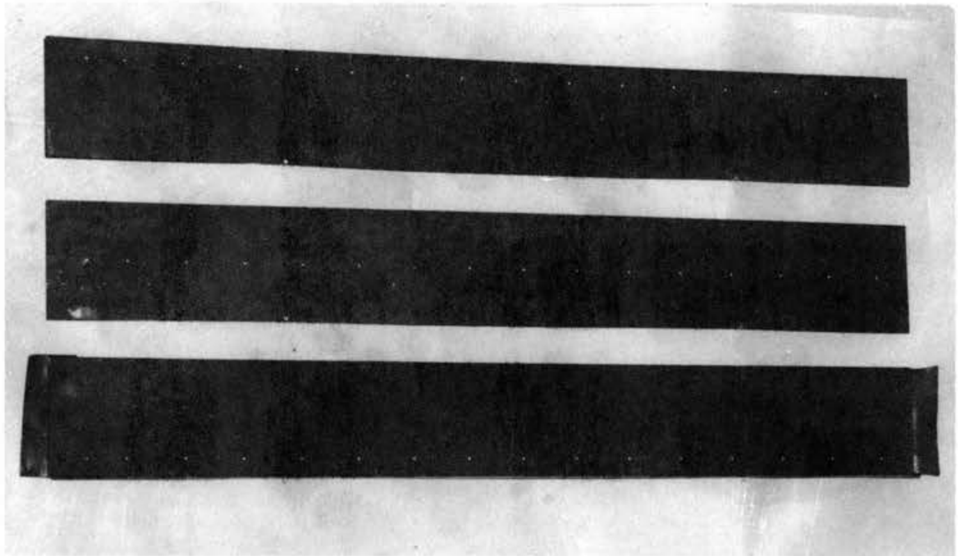


Figure 14. Horizontal barrier positioned in the water reservoir.

projection about 1/4 inch above the water surface was obtained. Widths used were .13, 2, 4, and 6 inches. The narrowest width--.13 inch--represented a double thickness of sheet metal. This width was required to obtain adequate strength. Film coverage in the lee of the barrier was negligible so measurements were taken at the downwind end of the reservoir. Air velocities from 860 fpm to 1125 fpm were used. Higher velocities were required because the length of water surface was reduced to 12 feet by placing the barrier at the center of the reservoir. A 90°F water temperature was maintained. Data from these tests are given in Appendix A-8.

Studies of flow around cylinders showed that when minute holes were drilled in the cylinder and a small volume of air drawn from the air stream, the flow pattern changed. Less turbulence was experienced on the downwind surface of the cylinder. Application of the reverse of this principle to barriers could be made by making small perforations in the barrier and permitting a small amount of air to pass through. Three barriers were perforated (Figure 15-A). Small holes--3/32 inch in diameter--were drilled one inch from the bottom of the barrier. Open areas of 0.0387, 0.0718, and 0.1076 percent of total barrier area were provided. Vertical, 6 inch barriers were used for these tests. Water temperature was maintained at 90°F and air velocities from 610 fpm to 870 fpm were used. Data from these tests are given in Appendix A-9.

Position of the perforations was a variable to be considered. Shown in Figure 15-B are the three elevations used for these tests. Six inch vertical barriers with 0.0387 percent perforated area were used. Air velocities from 605 fpm to 870 fpm were used. A 90°F water temperature was maintained. Data from these tests are listed in Appendix A-10.



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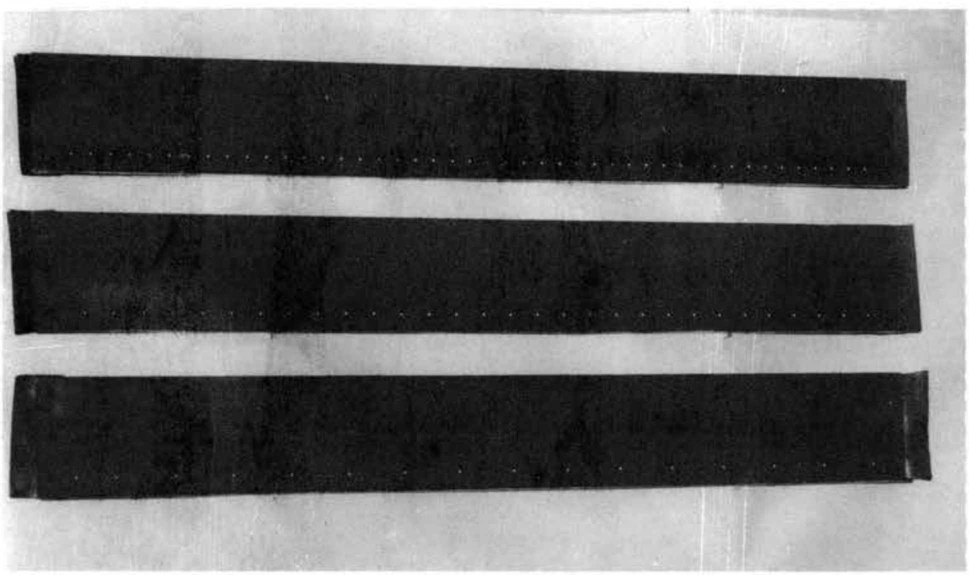

B

Figure 15. Perforated barriers. Perforation diameter is 3/32 inch. Barriers are 6 inches high. Picture A. Lower, center, and upper barriers have holes 1, 3, and 5 inches respectively from the floor. Percent open area is 0.0387. Picture B. Lower, center, and upper barriers have 0.0387, 0.0718, and 0.1076 percent open area respectively.

Successive barrier effect was considered. For this part of the study, the ratio of barrier height to distance was maintained constant. Barrier heights of 1, 2, 3, 4, and 6 inches were used. Figure 16 shows three 4 inch barriers installed in the wind tunnel. Water temperature was maintained at 90°F for these tests. Air velocities ranged from 805 fpm to 1920 fpm. Data from these tests are given in Appendix A-11 and A-12.

Water Temperature

Limited information was available concerning the effect of temperature on the film strength. Most of the laboratory work was carried out at a single selected temperature.

Water temperatures encountered in the field range from slightly above freezing to over 90°F. Usually evaporation retarding practices have been used during moderate to high water temperatures. With this as a guide, it was decided that a temperature of 50°F was a satisfactory minimum that could be successfully handled under available laboratory conditions. Previous studies carried out by the author showed that it was difficult to detect the film location at high temperatures. A maximum of 100°F was selected. This was about 20°F below the melting point of hexadecanol.

Water temperature was reduced to 50°F by the combination of pumping chilled water through the heat exchanger and dissolving crushed ice in the water in the reservoir. Hot water was then pumped through the heat exchanger and readings taken to determine film coverages at 5°F temperature increments. Air velocity was maintained constant during each test run. Velocities used in conducting the complete set of temperature tests ranged from 565 to 940 fpm. Appendix A-13 contains these data.

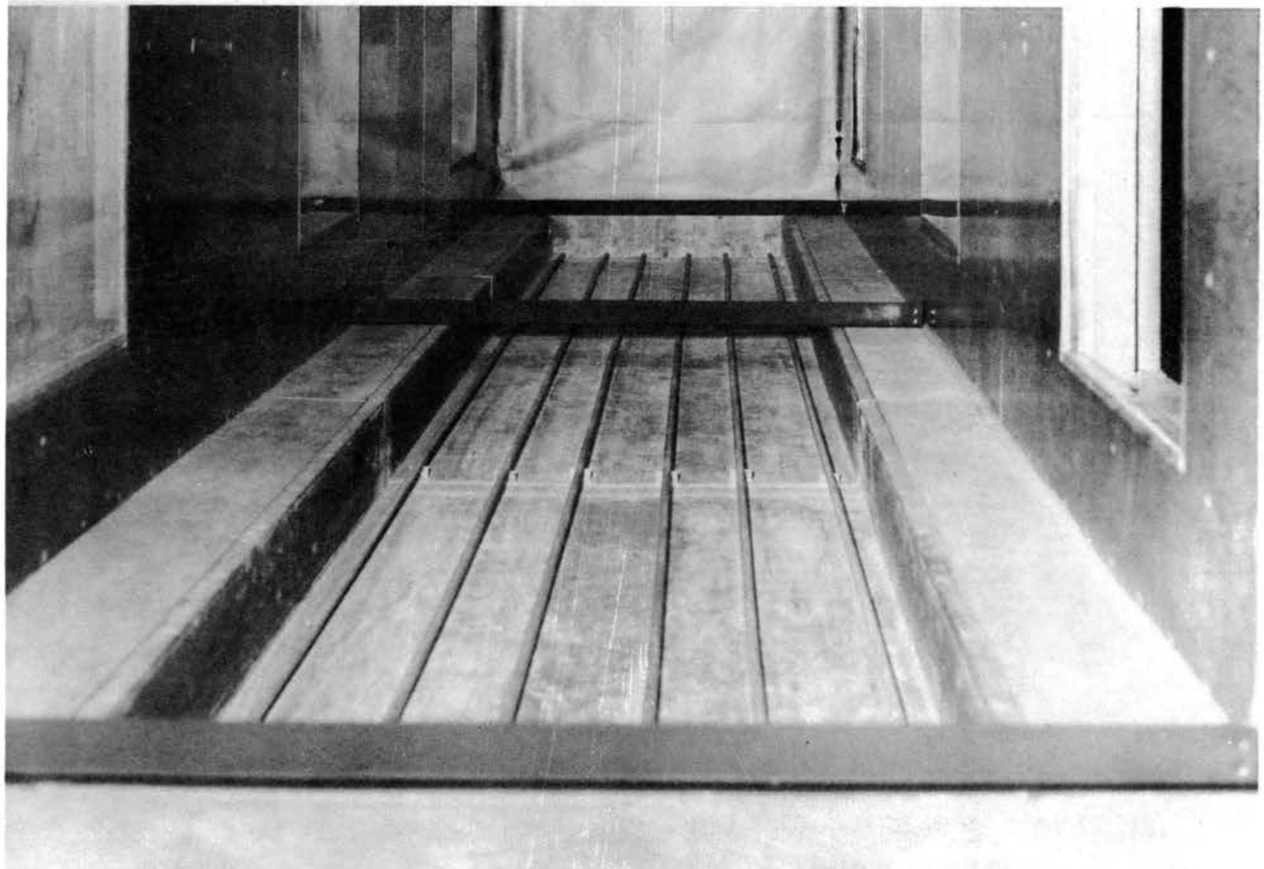

Figure 16. Vertical barriers installed in wind tunnel. Water and film flow underneath the center barrier was prevented by a sheet metal strip--not visible in this picture. Barrier height is 4 inches.

CHAPTER VI

ANALYSIS OF DATA

Velocity Profile Effects

Data were taken to relate air velocity, density, and viscosity to film coverage for two velocity profiles. The first data were for $v = V(y/\Delta)^{.17}$, and the second data were for $v = V(y/\Delta)^{.25}$ (Appendix A-4 and A-5). Water temperature was maintained constant so collapse pressure did not change. Film coverage (XF) was designated the ordinate and V/ν the abscissa. A linear regression analysis was used to determine the line of best fit. Each set of data was analyzed separately and then the two sets were combined and analyzed. Table III gives the results of these analyses.

TABLE III

RESULTS OF THE LINEAR REGRESSION ANALYSIS APPLIED TO DATA FROM TWO VELOCITY PROFILES

Data Set	Slope	Y-Intercept	Correlation Coefficient
$v = V(y/\Delta)^{.17}$	1.641×10^6	-12.96	.987
$v = V(y/\Delta)^{.25}$	1.678×10^6	-13.38	.998
Combined	1.662×10^6	-13.20	.993

The upper limit of the slope for the combined data was 1.727×10^6 and the lower limit was 1.59×10^6. This was at a 95 percent confidence level.

It was noted that the calculated slopes for the individual data sets were both within these limits. This suggested that a test be performed to determine if there was a significant difference between the two data sets.

In an Analysis of Covariance, two assumptions were necessary. First, the two sets of data were drawn from normal population with a common variance, and second, the two regression coefficients were the same. It was necessary to show that the elevations of the two lines were the same and were described by the combined analysis. Table IV shows the data used for the Analysis of Covariance.

F tests were performed to test the regression coefficients and elevation of the lines. The two tests are as follows:

$$F = \frac{\text{mean square for regression}}{\text{mean square within samples}} = \frac{.00023}{.00056} = .411$$

$$F_{1,\ 32(.05)} = 4.15$$

$$F = \frac{\text{mean square for adjusted means}}{\text{mean square for common}} = \frac{.00005}{.00055} = .0909$$

$$F_{1,\ 33(.05)} = 4.14$$

Comparing the calculated F value of 0.411 to the tabulated value of 4.15 for 1 and 32 degrees of freedom showed the differences to be non-significant. It was accepted that the regression coefficients were the same. The F value computed for determining difference in the Y-intercept was 0.0909. When compared to 4.14 for 1 and 33 degrees of freedom, it was noted that the difference in intercepts lacked significance.

Based on the analyses performed on the data taken for this portion of the laboratory experiment, it was concluded that the slope of the velocity profile from the 1 inch position to the center line of the wind tunnel did not significantly affect the hexadecanol film cover maintained

TABLE IV

SUMMARY OF DATA AND COMPUTATIONS FOR THE
ANALYSIS OF COVARIANCE
XF VERSUS V/ν

Data Set	f	Σx^2	Σxy	Σy^2	Reg. Coef.	f	$\Sigma y^2 - (\Sigma xy)^2/\Sigma x^2$	Mean Square
$(y/\triangle)^{.17}$	14	$.20881x10^{-9}$	$.3427x10^{-3}$	$.57724x10^{3}$	$1.641x10^{6}$	13	.01460	.00112
$(y/\triangle)^{.25}$	20	$.28381x10^{-4}$	$.47631x10^{-3}$	$.80268x10^{6}$	$1.678x10^{6}$	19	.00331	.00174
Within						32	.01791	.000561
Reg. Coef.						1	.00023	.00023
Common	34	$.49268x10^{-9}$	$.81911x10^{-3}$	$1.3799x10^{3}$	$1.662x10^{6}$	33	.01814	.00055
Adj Means						1	.00005	.00005
Total	35	$.49271x10^{-9}$	$.81912x10^{-3}$			34	.01819	

on the water surface.

Analysis of Pi Terms

Data given in Appendix A-13 were used to describe the effects of wind shear on the hexadecanol film. Analyses were performed to determine an adequate equation for the response surface to describe π_1 in terms of π_2 and π_3. Table V shows the coefficients obtained for various analyses using values of π_1, π_2, and π_3. Similar analyses were carried out with the data transformed into logarithmic form. Coefficients for these equations are shown in Table VI.

Several criteria were used to evaluate each equation that might prove useful. In the initial analyses, the coefficients were obtained, a value computed for the dependent variable, a percentage difference between the observed and computed value of the variable obtained, and a correlation coefficient calculated. Finally, the standard deviation between observed and computed values was determined. Tables V and VI show the results of these analyses.

Selection of the most suitable equation was then undertaken. The correlation coefficients from the multivariable program were examined first. A high correlation coefficient indicated the overall fit of data to the surface was good. The highest correlation coefficient obtained for π_1 versus π_2 and π_3 was .973. Inspection of the maximum percent difference between observed and computed values of π_1 showed the best equation to have a maximum difference of 16.0. The standard deviation ($.41\text{x}10^5$) was the lowest. It was concluded that the most accurate prediction equation from these analyses was

$$\pi_1 = 37.5\text{x}10^5 - 54.3\text{x}10^8\pi_2 + 33.4\text{x}10^{11}\pi_2^2 - 74.5\text{x}10^{13}\pi_2^3 - 2.67\text{x}10^4\pi_3 \qquad 6\text{-}1$$

TABLE V

COEFFICIENTS FOR THE ANALYSIS OF π_1 VERSUS π_2 AND π_3

	Constant $\times 10^{-5}$	π_2 $\times 10^{-8}$	π_2^2 $\times 10^{-11}$	π_2^3 $\times 10^{-13}$	π_3 $\times 10^{-4}$	π_3^2 $\times 10^{-4}$	π_3^3 $\times 10^{-4}$	R	Max. Error	SDEV $\times 10^{-5}$
1.	33.3	-43.4	21.2	-37.3	58.5	-33.1		.973	16.3	.410
2.	37.5	-54.3	33.4	-74.5	-2.67			.973	16.0	.410
3.	27.9	-30.0	8.06		107.	-59.4		.973	16.4	.414
4.	17.3	-9.6	1.34		-.68			.969	16.8	.446
5.	16.8	-5.4			-108.	125.	-45.8	.971	16.0	.433
6.	16.1	-8.1			26.2	-4.23		.968	16.9	.449
7.	15.8	-7.44			13.4			.968	17.0	.450

TABLE VI

COEFFICIENTS FOR ANALYSIS OF π_1 VERSUS π_2 AND π_3 WITH DATA TRANSFORMED INTO LOGARITHMIC FORM

	Constant	π_2	π_2^2	π_2^3	π_3	π_3^2	π_3^3	R	Max Error	SDEV $x10^{-5}$
1.	11.7	.201	.116	-.0285	-.0098	-40.9		.975	1.22	.458
2.	-39.6	-11.2	.0261	.0759	.119			.978	1.26	.492
3.	-8.0	-4.73	.225		.0055	-.248		.976	1.20	.466
4.	-36.8	-14.0	-.979		-.0959			.973	1.25	.461
5.	1.93	-1.75			.0852	-.875	-.487	.983	1.25	.372
6.	1.19	-1.86			.952	.976		.976	1.21	.459
7.	10.4	-.421			-.430			.962	1.46	.497

Figure 17 shows the surface obtained with this equation.

In an attempt to obtain a simpler expression, the data were transformed to natural logarithmic form. The equation that gave the highest correlation coefficient (Table VI) and lowest standard deviation (.372x10^5) for observed versus calculated π_1 values was

$$\ln \pi_1 = 1.93 - 1.75 \ln \pi_2 - .0852 \ln \pi_3 - .875(\ln \pi_3)^2 - .487(\ln \pi_3)^3 \qquad 6\text{-}2$$

The maximum difference between the observed and calculated values of $\ln \pi_1$ was 1.46 percent. Although the correlation coefficient was not as high as for other equations, the simple equation

$$\ln \pi_1 = 10.4 - .421 \ln \pi_2 - .430 \ln \pi_3 \qquad 6\text{-}3$$

gave a standard deviation of .497x10^5 for observed versus calculated values of π_1. This was not much greater than the .372x10^5 for the more complicated equation immediately above. The simpler equation can be expressed as

$$\pi_1 = \frac{3.26\text{x}10^4}{\pi_2^{.42}\ \pi_3^{.43}} \qquad 6\text{-}4$$

Figure 18 shows the response surface obtained with this equation.

The equation providing the lowest percentage difference between $\ln \pi_1$ observed and $\ln \pi_1$ calculated gave a value of 1.20 percent. The corresponding standard deviation for π_1 observed versus π_1 calculated was .466x10^5. This equation was

$$\ln \pi_1 = -8.0 - 4.73 \ln \pi_2 + .225(\ln \pi_2)^2 + .005 \ln \pi_3 - .248(\ln \pi_3)^2 \qquad 6\text{-}5$$

It was apparent that this equation was unwieldy and less desirable than 6-4.

The only other equation worthy of mention in this group was

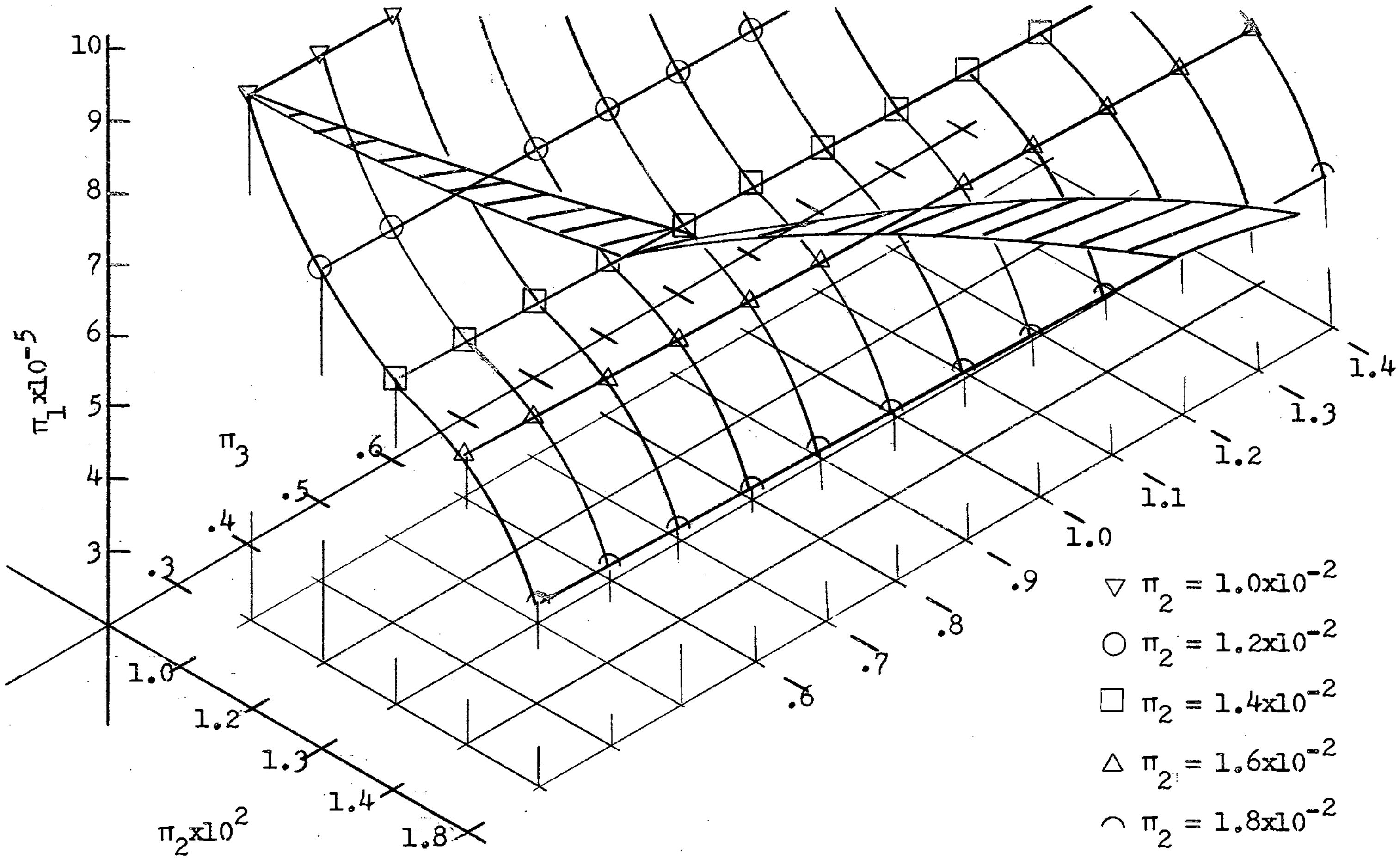

Figure 17. Response Surface from Equation 6-1. Lined area represents the range of the laboratory experiments.

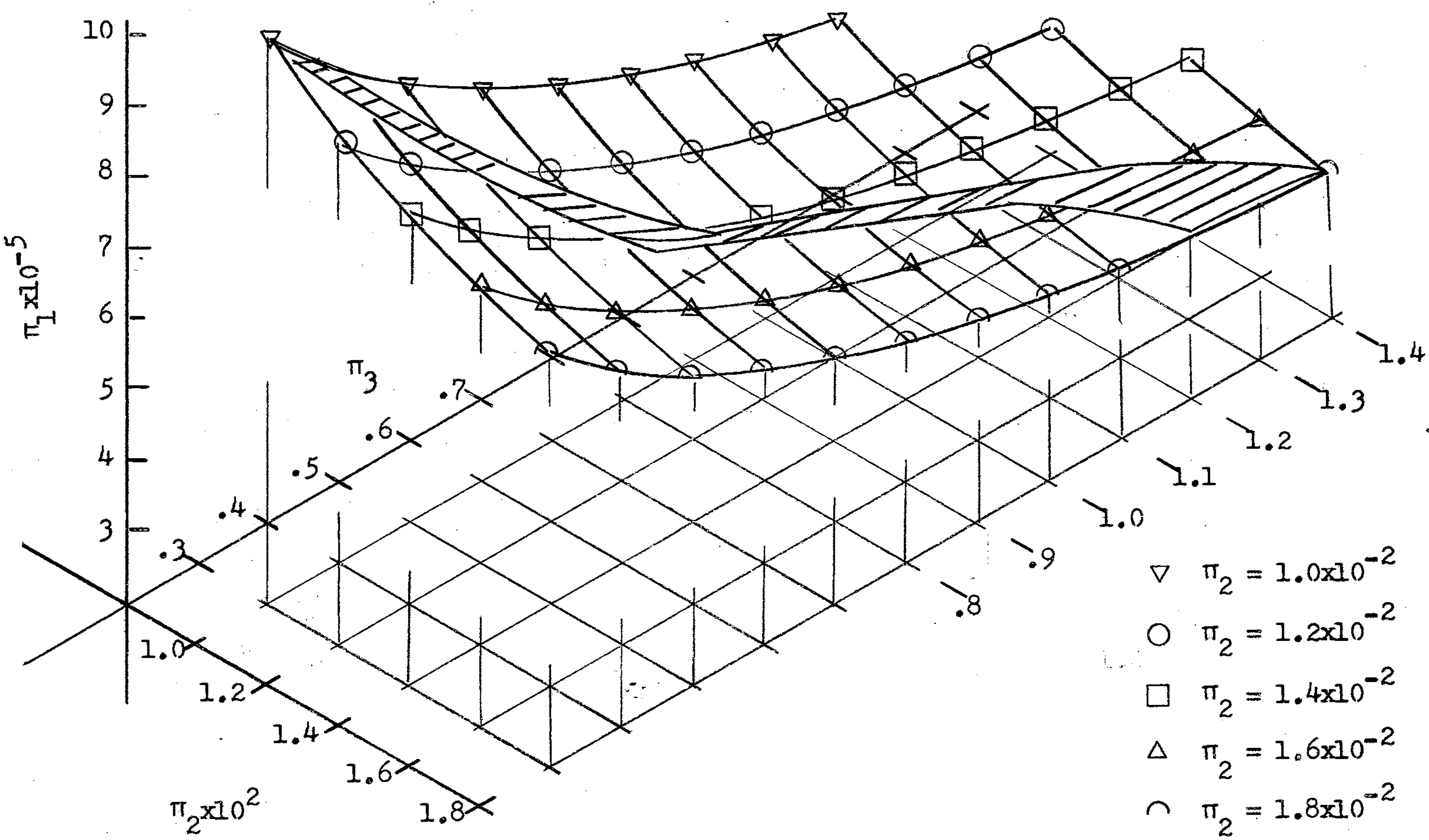

Figure 18. Respose Surface from Equation 6-4. Lined area represents the range of the laboratory experiments.

$$\pi_1 = 15.8\text{x}10^5 - 7.44\text{x}10^8\ \pi_2 + 13.4\text{x}10^4\ \pi_3 \qquad 6\text{-}6$$

Figure 19 shows the response surface for this equation.

This relatively simple equation gave a maximum of 16.97 percent difference between observed and calculated values of π_1 with a standard deviation of $.450\text{x}10^5$.

Equation 6-4 probably would be selected as the best equation to use because of its simplicity. Comparison of Figures 17, 18, and 19 indicated that less error would be introduced if calculations were made outside the range of experimental velocities. Difficulties encountered in obtaining exact air velocity measurements and accurately locating the edge of the hexadecanol film suggested that this equation was adequate. Assuming precise measurements, equation 6-2 could be used on a computer and more accurate answers obtained.

Analysis of Pertinent Quantities

Analyses of the data in terms of film coverage, air velocity, air viscosity, air density, and collapse pressure of the film was carried out. Inspection of Table VII shows that the coefficients on line 7 provided the most accurate description of film coverage; however, the equation obtained using these values was difficult to utilize. The simpler equation

$$XF = 52.7 - 1.76\ V - 2.22\text{x}10^5\,\nu + 5.21\text{x}10^3\ Pc \qquad 6\text{-}7$$

permitted a maximum difference of 38.5 percent between observed and calculated values of XF. The standard deviation was .95. The simpler equation was less accurate while the more accurate equation was difficult to handle.

Data were then transformed to logarithmic form. Somewhat more

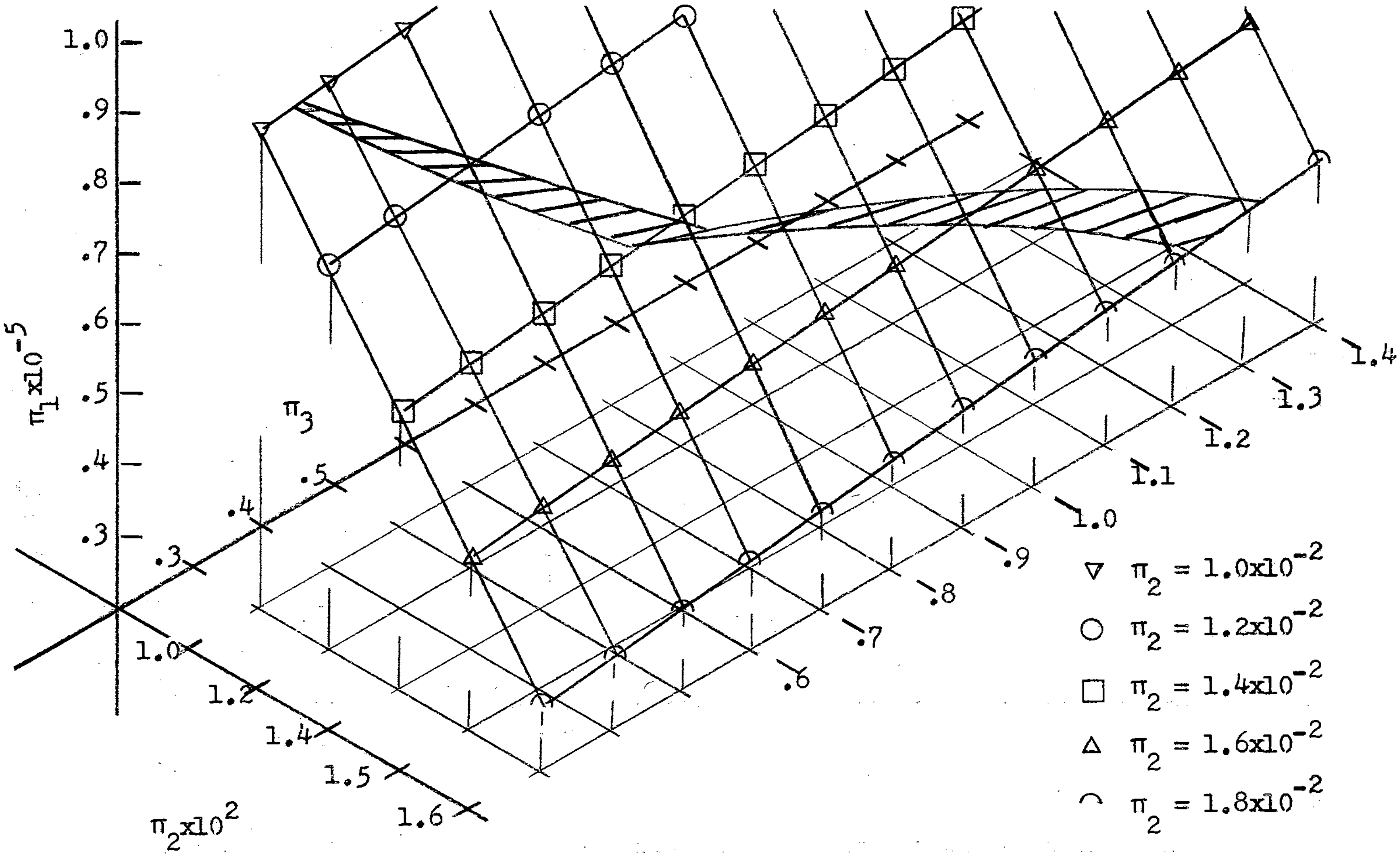

Figure 19. Response Surface from Equation 6-6. Lined area represents the range of the laboratory experiments.

TABLE VII

COEFFICIENTS OBTAINED IN THE ANALYSIS OF XF VERSUS V, ν, AND Pc

	Constant $\times 10^{-3}$	V	V^2	V^3	ν $\times 10^{-6}$	ν^2 $\times 10^{-10}$	Pc $\times 10^{-3}$	Pc^2 $\times 10^{-6}$	R	Max Error Between Obs & Cal (%)	XF Obs Vs XF Comp. Slope	R	SDEV
1.	1.24	-5.12	.137		-13.6	3.91	-8.31	2.28	.941	17.9	.988	.994	.517
2.	1.20	-5.12	.137		-13.5	3.86	6.97		.994	18.4	.988	.994	.516
3.	.04	-5.64	.157		.08		6.91		.991	15.5	.988	.991	.635
4.	1.70	-1.72			-18.9	5.40	-13.1	2.79	.986	23.7	.972	.986	.796
5.	.008	-1.76			-.22		41.6	-5.43	.980	40.6	.960	.980	.952
6.	.0527	-1.76			-.22		-5.21		.980	38.5	.960	.980	.954
7.	1.13	-22.2	1.55	-.0381	-11.8	3.42	-1.12	1.32	.995	15.5	.990	.995	.483
8.	1.10	-22.3	1.55	-.0383	-11.7	3.40	7.76		.995	15.8	.990	.995	.482
9.	.11	-30.3	2.20	-.0552	.10		8.05		.992	17.9	.985	.993	.578

satisfactory results were obtained by this method (Table VIII). The equation

$$\ln XF = 34.9 - 2.38 \ln V + 1.06 \ln \tau + 3.09 \ln Pc \qquad 6\text{-}8$$

gave a maximum difference of 8.12 percent between observed and calculated values of XF. The standard deviation was .55. The slope of the line representing XF calculated versus XF observed was 1.02 with a correlation coefficient of .994. This equation was then written as

$$XF = 1.45\text{x}10^{15} \frac{\tau^{1.06}\, Pc^{3.09}}{V^{2.38}} \qquad 6\text{-}9$$

which can easily be used to calculate film coverage.

Inspection of lines 3 and 8 in Table VIII reveals that lower standard deviations and maximum percentage differences can be obtained at the expense of using more complicated equations. Selection of the equation to use depends on computation facilities available.

Vertical Barrier Influence

A series of tests was conducted with one barrier at the upwind end of the reservoir. Linear regression analyses were carried out with π_1 as the ordinate and π_4 as the abscissa. Hexadecanol film coverage at the downwind end of the reservoir was the length term in π_1. The null hypothesis that the slope of the line describing this relationship was zero was tested by calculating the T value for n-2 degrees of freedom and comparing this value with the tabulated T value at a 95 percent confidence level. In all cases, except one, it was not possible to reject the null hypothesis for downwind film coverage. Table IX contains the results of these analyses. It was concluded that with a single barrier at the upwind end, barrier height had no significant

TABLE VIII

COEFFICIENTS FOR ANALYSIS OF XF VERSUS V, ν, AND Pc WITH THE DATA TRANSFORMED INTO LOGARITHMIC FORM

	Constant	V	V^2	V^3	ν	ν^2	Pc	Pc^2	R	Max Error Between Obs & Cal (%)	XF Obs Vs XF Comp Slope	R	SDEV
1.	2.61	4.24	1.34		2.23	.175	-3.95	-.58	.995	5.52	.985	.995	.470
2.	2.19	4.23	1.34		-2.26	-.0845	2.72		.995	5.46	.985	.995	.471
3.	8.58	4.23	1.33		-.796		2.72		.995	5.45	.985	.995	.471
4.	.71	-2.38			-2.23	-.189	-3.89	-.61	.992	8.15	1.02	.994	.547
5.	11.3	-2.38			1.06		-5.18	-.72	.992	8.15	1.02	.994	.547
6.	34.9	-2.38			1.06		3.09		.992	8.12	1.02	.994	.547
7.	-132.	-71.2	29.34	4.15	-64.0	-3.73	25.5	1.98	.996	5.46	.988	.996	.400
8.	-202.	-111.	45.67	-6.35	-73.5	-4.32	2.95		.997	5.78	.990	.996	.396
9.	-261.	272.	-110.	14.69	-6.27		2.09		.992	7.91	.973	.973	1.098

TABLE IX

RESULTS OF THE LINEAR REGRESSION ANALYSIS COMPARING π_1 AND π_4

Ave. Vel. (fpm)	T Calculated	T Tabulated	Reject Null Hypothesis
	Downwind End of Reservoir Individual Tests		
618	1.749	12.706	No
676	1.510	12.706	No
737	1.240	12.706	No
797	4.444	12.706	No
857	-1.278	12.706	No
620	-.270	12.706	No
678	-5.006	12.706	No
737	11.964	12.706	No
799	3.556	12.706	No
862	.237	12.706	No
618	.013	12.706	No
676	-1.443	12.706	No
737	-2.348	12.706	No
797	4.761	12.706	No
857	36.384	12.706	Yes
	Combined Data		
619	.901	2.365	No
676	-.517	2.365	No
737	.944	2.365	No
798	2.131	2.365	No
857	.781	2.365	No

effect on film coverage at the downwind end of the reservoir. The one instance that did show significance was assumed to be caused by excessive experimental error. Consistency of the other individual tests and that of the combined data support this assumption.

Film coverage at the upwind end of the reservoir, in the lee of the barrier, was influenced by barrier height. The equation relating π_1' and π_4 for an average velocity of 610 fpm was[1]

$$\pi_1' = 1.44 \times 10^7 \ \pi_4^{.969} \qquad 6\text{-}10$$

At an average velocity of 855 fpm the describing equation was

$$\pi_1' = 1.35 \times 10^7 \ \pi_4^{.90} \qquad 6\text{-}11$$

The combined analysis gave the equation

$$\pi_1' = 1.39 \times 10^7 \ \pi_4^{.934} \qquad 6\text{-}12$$

Comparison of these equations presented the possibility of using the combined equation to describe both situations. An Analysis of Covariance was performed. This analysis is summarized in Table X.

The F tests performed were as follows:

$$F = \frac{.2548}{.02964} = 8.6 \qquad F_{1,\,14} = 4.60$$

$$F = \frac{.0035}{.04465} = .0783 \qquad F_{1,\,15} = 4.54$$

The first F test showed that the slopes were significantly different while the second test showed that the Y-intercepts of the lines were not significantly different. Values for π_1' were calculated using the three equations given above. It was noted that for the lowest barrier height the magnitude of π_1' obtained with the equations 6-10 and 6-11 did not vary over 15 percent from that of the equation obtained using the combined

---

[1] π_1' was the selected designation when film coverage was measured in the lee of the barrier.

TABLE X

SUMMARY OF DATA AND ANALYSIS OF COVARIANCE FOR COMPARISON OF EQUATIONS RELATING π_1' TO π_4 (LEE OF BARRIER) AT 610 AND 855 FPM

Data Set	f	Σx^2	Σxy	Σy^2	Reg. Coef.	f	$\Sigma y^2 - (\Sigma xy)^2 / \Sigma x^2$	Mean Square
610 fpm	8	1.8518	1.7938	1.7597	.969	7	.0221	.00361
855 fpm	8	1.8518	1.6659	1.8916	.90	7	.3929	.0561
Within						14	.4150	.02964
Reg Coef						1	.2548	.2548
Common	16	3.7036	3.4596	3.9014	.934	15	.6698	.04465
Adj Means						1	.0034	.0034
Total	17	3.7034	3.4593	3.9045		16	.6733	.04208

$\Sigma X = -78.7061$ $\Sigma Y = 222.568$

$(\Sigma X)^2/18 = 344.1472$ $\Sigma X \Sigma Y/18 = 973.1922$ $(\Sigma Y)^2/18 = 2752.0285$

$$\Sigma x^2 = 347.8506 - 344.1472 = 3.7034$$

$$\Sigma xy = -969.7329 + 973.1922 = 3.4593$$

$$\Sigma y^2 = 2755.9331 - 2752.0285 = 3.9045$$

$$F = \frac{.2548}{.02964} = 8.596 \qquad F_{1,\,14} = 4.60$$

$$F = \frac{.0035}{.04465} = .0783 \qquad F_{1,\,15} = 4.54$$

data. This variation was about 10 percent for the highest barrier. It was concluded that the equation (6-12) resulting from the combined analysis was acceptable for all conditions within the range tested. Data are tabulated in Appendix A-6.

Observation of the film performance presented another point for consideration. For a time after separation of the hexadecanol film, quantities of the film left the leeward side of the barrier and moved across the surface to the downwind end of the reservoir. Calculations were made to determine the ratio of measured film coverage to barrier heights. These ratios ranged from a low of 10.8 to a high of 14.4. A linear regression analysis was applied to determine if the ratio of film coverage to barrier height was significantly influenced by wind velocity. The comparison of the tabulated T value (2.00) to the calculated T value (1.77) showed that it was not possible to reject the null hypothesis that the slope of the line relating wind velocity and film coverage-barrier height ratio was zero. It was concluded that velocity did not significantly influence the above ratios.

Data taken with barriers at the upwind and downwind end of the reservoir was analyzed next. The first analysis relating π_1'' to π_4 with barriers at both ends of the reservoir resulted in a family of curves.[1] A second analysis was made relating π_1'' to π_2 and π_4. From the several possible equations, the best one was selected. The relationship was

$$\pi_1'' = 13.3\text{x}10^5 - 95.5\text{x}10^7\pi_2 + 17.3\text{x}10^{10}\pi_2^2 + 73.2\text{x}10^6\pi_4 - 11.0\text{x}10^8\pi_4^2 \qquad 6\text{-}13$$

A correlation coefficient of .995 was obtained in this analysis.

[1] π_1'' indicated total film coverage--downwind film coverage plus film coverage in the lee of a barrier.

Maximum difference between observed and computed values of π_1'' was 10.4 percent. Results of this analysis are plotted in Figure 20.

The T test for downwind coverage showed that barrier height did not significantly influence the amount of film that could be maintained when a single barrier was used upwind. However, the introduction of the second barrier did prove significant.

The first analysis of π_1 versus π_4 resulted in a family of curves. π_1 was then related to π_2 and π_4. A correlation coefficient of .997 was the best obtained for this multivariable analysis. The resulting equation was

$$\pi_1 = 18.4x10^5 - 12.2x10^8\pi_2 + 19.7x10^{10}\pi_2^2 + 31.7x10^6\pi_4 - 58.3x10^7\pi_4^2 \qquad 6\text{-}14$$

Maximum difference between observed and computed values of π_1 was 10.2 percent. Figure 21 is a plot of this analysis. Transformations of data into logarithmic form did not produce an equation having a correlation coefficient as high as .997. No equations of this form are reported.

The installation of barriers at both ends of the reservoir produced different effects than when a single upwind barrier was used. As wind velocity increased, downwind coverage decreased; therefore, total coverage was influenced as wind velocity changed. Data are listed in Appendix A-12.

Wide Barrier Effect

The effect of low barriers of variable width was evaluated by analyzing π_1 against π_5. A linear regression analysis was performed, and a T value calculated and compared to the tabulated T value. For each of the individual tests, it was not possible to reject the null hypothesis

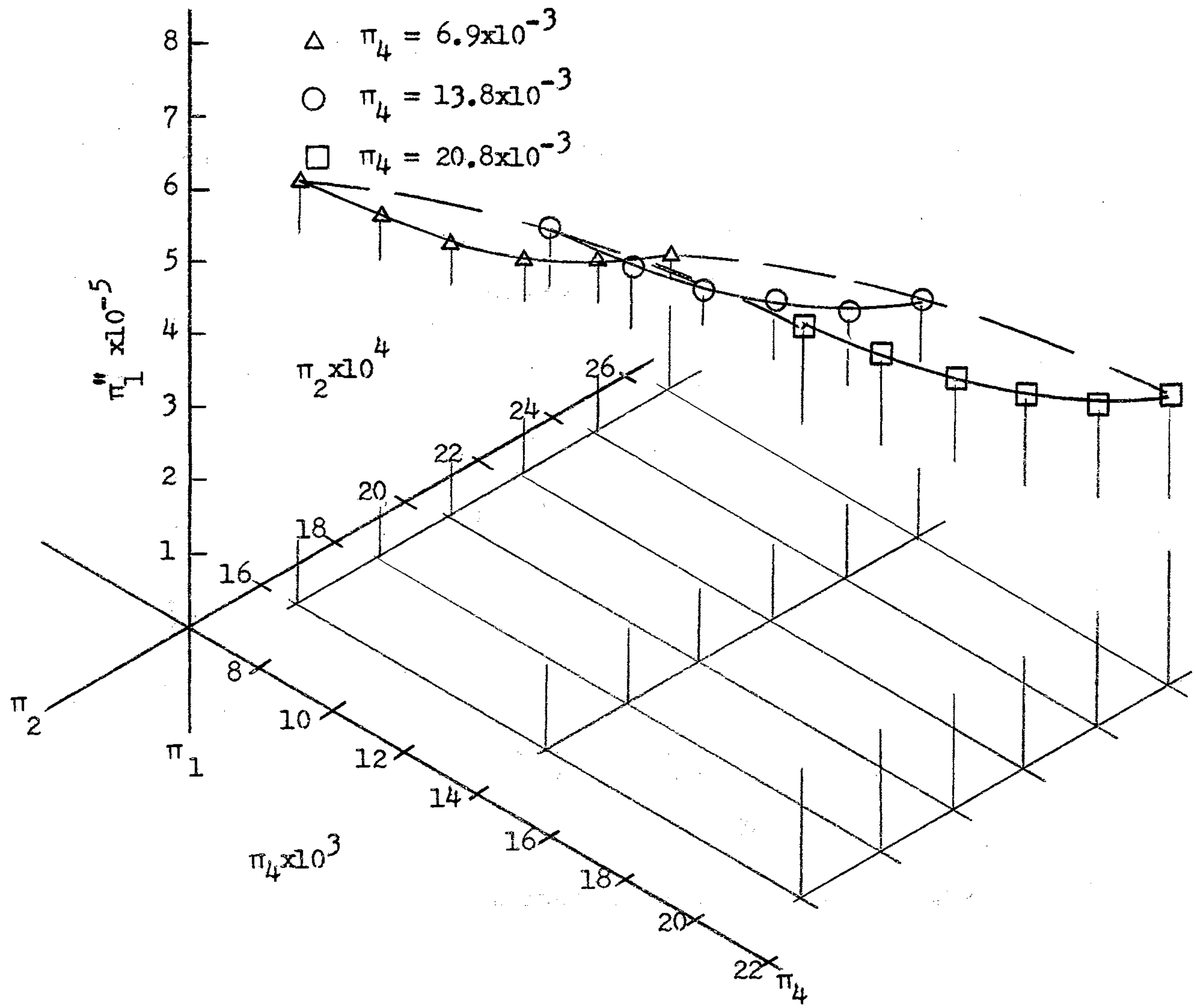

Figure 20. Response Surface for Equation 6-13.

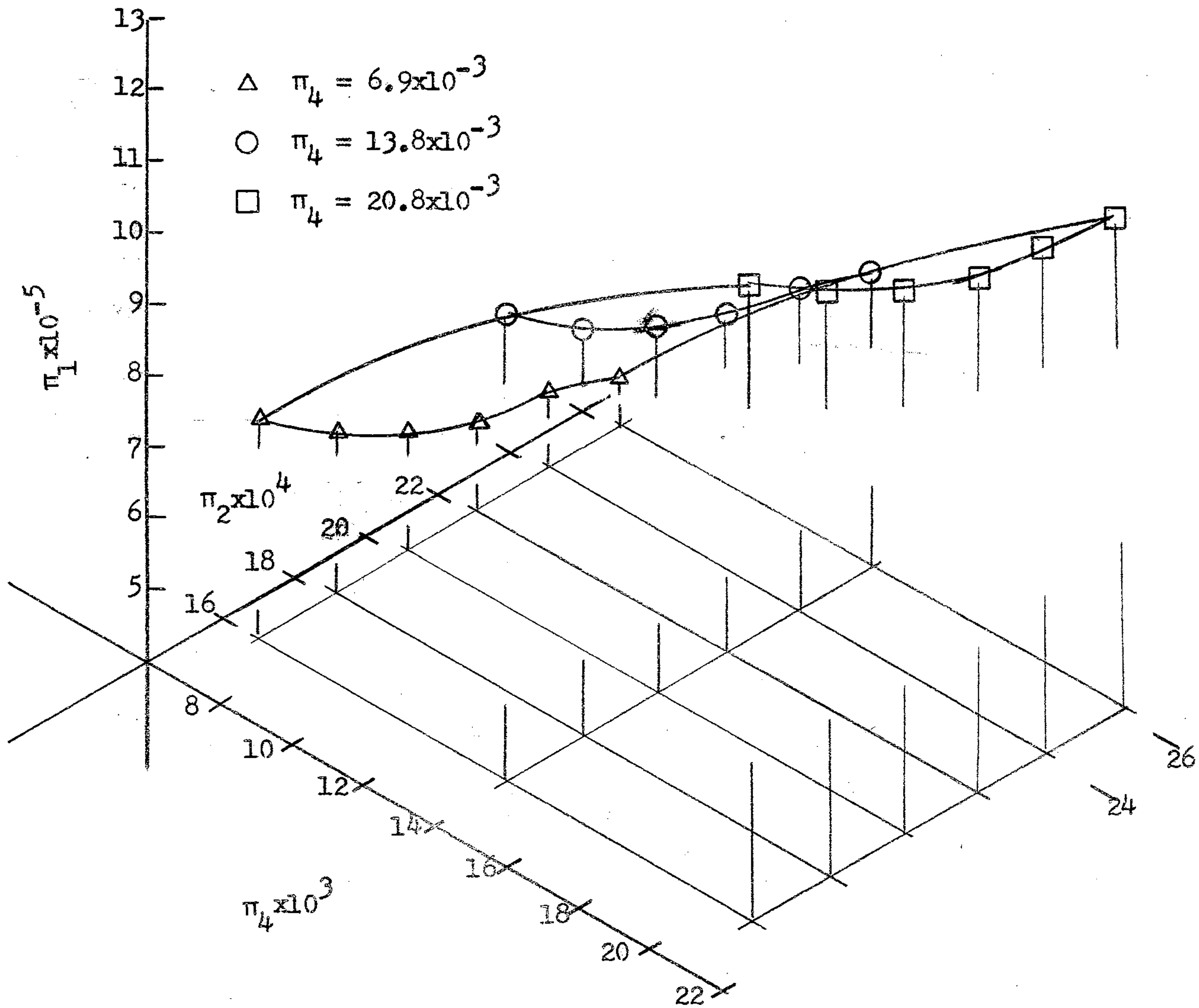

Figure 21. Response Surface for Equation 6-14.

that the slope of the line was equal to zero. Data at each velocity level were combined and the analysis repeated. It was not possible to reject the null hypothesis when the combined data were used. Data are tabulated in Appendix A-8. Table XI lists the results of this analysis. Figures 22 and 23 show this analysis.

TABLE XI

LINEAR REGRESSION ANALYSIS COMPARING π_1 AND π_5

Average Free Stream Velocity (fpm)	T Calculated	T Tabulated	Rejected Null Hypothesis
	Individual Tests		
862	-1.925	4.303	No
1115	.440	4.303	No
859	-1.547	4.303	No
1108	2.708	4.303	No
844	-2.077	4.303	No
1112	-.649	4.303	No
	Combined Data		
855	-2.001	2.228	No
1112	.949	2.228	No

Perforated Barrier

A linear regression analysis was performed on the individual tests and on the combined data for velocities averaging 614 and 858 fpm. The method of least squares was used. π_1 was plotted as a function of π_8. π_8 was defined as the percent of barrier that was open area. T values were calculated and compared with tabulated T values to test the null hypothesis that the slope of the line was zero. In two instances the calculated T exceeded the tabulated T and it was possible to reject the

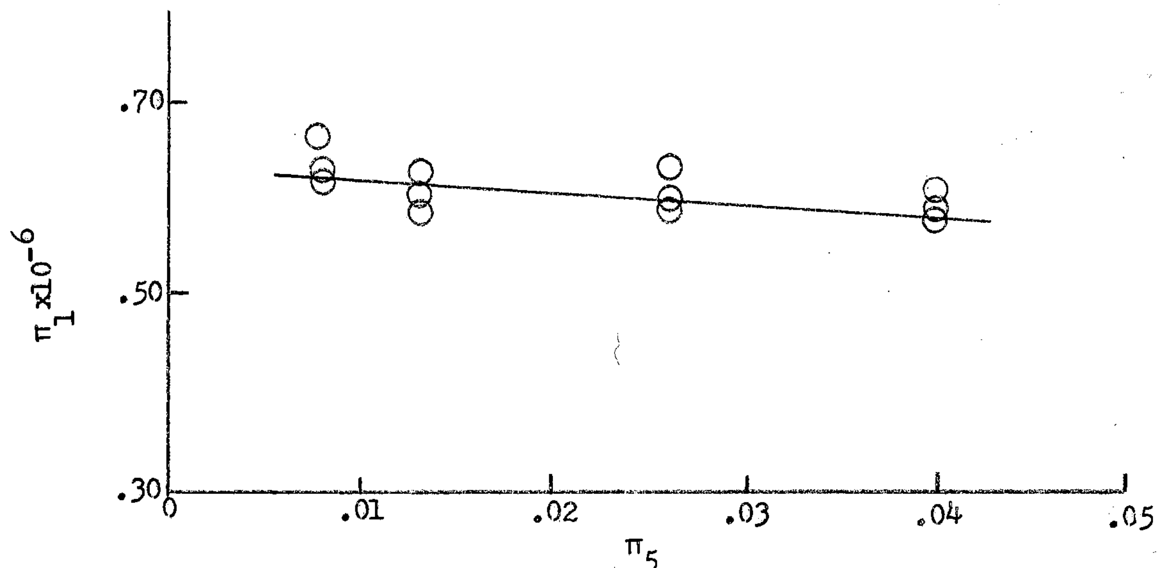

Figure 22. Plot of π_1 versus π_5. Air velocity was approximately 855 fpm.

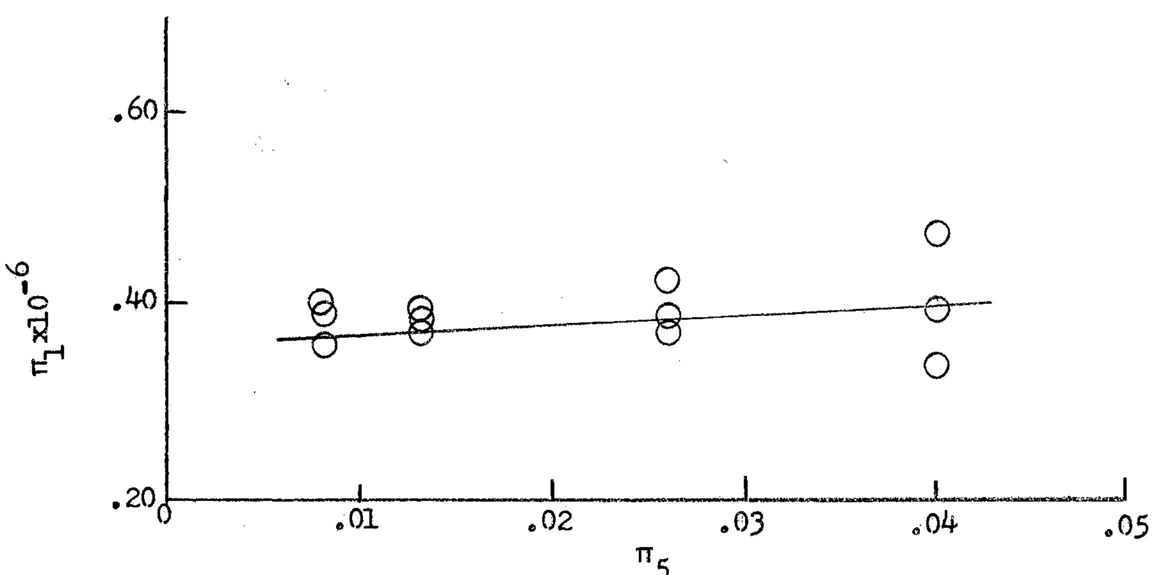

Figure 23. Plot of π_1 versus π_5. Air velocity was approximately 1112 fpm.

null hypothesis. However, in all other individual tests it was not possible to reject the null hypothesis. It was concluded that the two individual tests were not truly indicative of the entire test series and more reliance was placed on the combined data. Data are listed in Appendix A-9. Table XII shows the result of this analysis. Plots in Figures 24, 25, 26, and 27 contain this analysis.

An analysis similar to that described above was carried out for π_1 versus π_6. The same two velocity levels were used. In this case, π_6 was the ratio of the distance between the floor and perforation height to the total height of the barrier. Comparison of calculated T values to the tabulated T values for analysis of each test and the combined data at the two velocity levels showed that it was not possible to reject the null hypothesis. Table XIII shows the results of this analysis. Data are located in Appendix A-10. Based on tests performed, it was not possible to say that amount of perforated area or position of the perforation significantly influenced film coverage. Plots shown in Figures 28, 29, 30, and 31 give this analysis.

Sloping Barriers

In analyzing the effect of sloping barriers, π_1 was plotted against π_7 (the angle of slope given in radians). A linear regression analysis was carried out using the least squares method. The T value was calculated for each test and for the combined data for the three replicates at each velocity level. Results of this test are shown in Table XIV. It was observed that in no instance did the calculated T value exceed that of the tabular T value. In the test, the null hypothesis, that the slope of the line of best fit was zero, could not be rejected. It was

TABLE XII

LINEAR REGRESSION ANALYSIS COMPARING π_1 AND π_8

Average Free Stream Velocity (fpm)	T Calculated	T Tabulated	Rejected Null Hypothesis
	In Lee of Barrier Individual Tests		
610	1.717	12.706	No
853	-.417	12.706	No
612	-8.772	12.706	No
858	1.953	12.706	No
619	.686	12.706	No
864	-23.836	12.706	Yes
	Combined Data		
614	.613	2.365	No
858	-.339	2.365	No
	Downwind End of Reservoir Individual Tests		
610	10.874	12.706	No
853	18.022	12.706	Yes
612	-.888	12.706	No
858	-.449	12.706	No
619	-1.052	12.706	No
864	1.107	12.706	No
	Combined Data		
614	.140	2.365	No
858	.350	2.365	No

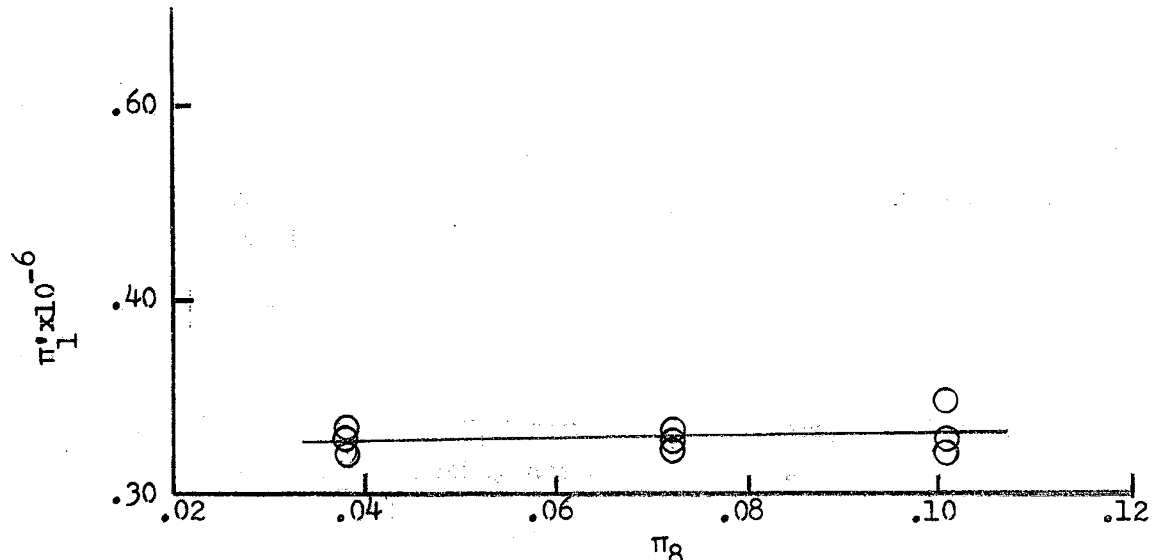

Figure 24. Plot π_1' versus π_8 for coverage in lee of the barrier. Velocity averaged 614 fpm.

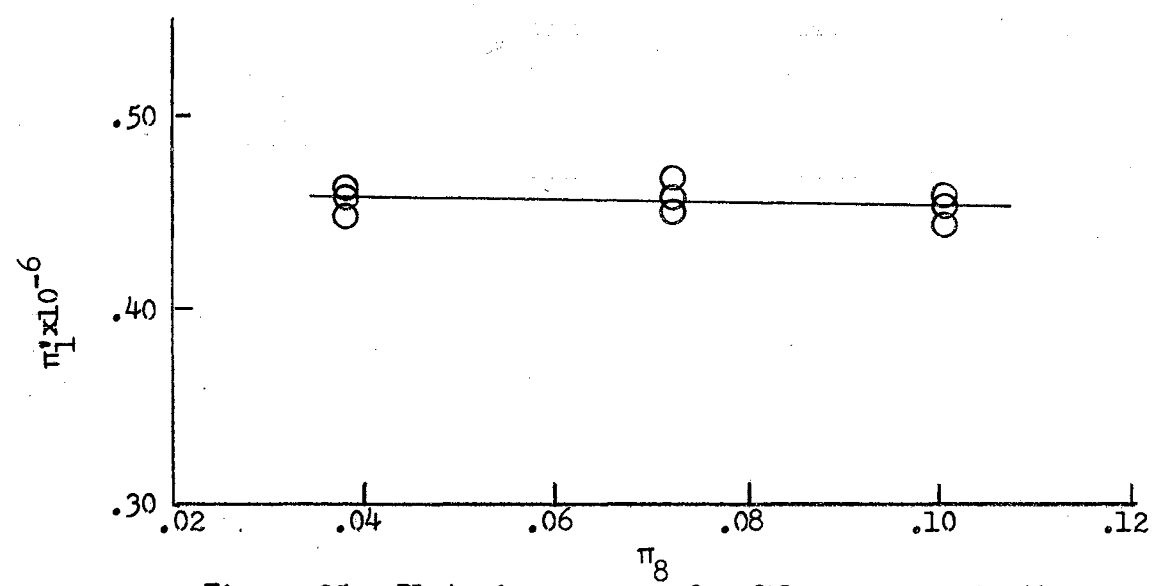

Figure 25. Plot π_1' versus π_8 for film coverage in the lee of the barrier. Velocity averaged 858 fpm.

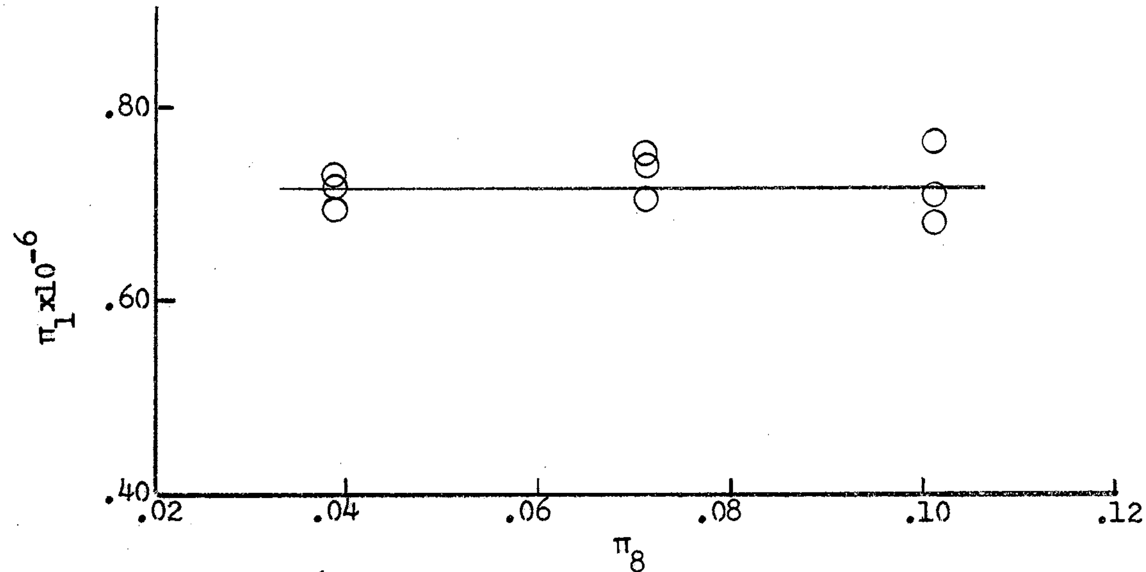

Figure 26. Plot of π_1 versus π_8. Film coverage at the downwind end of the reservoir. Velocity averaged 614 fpm.

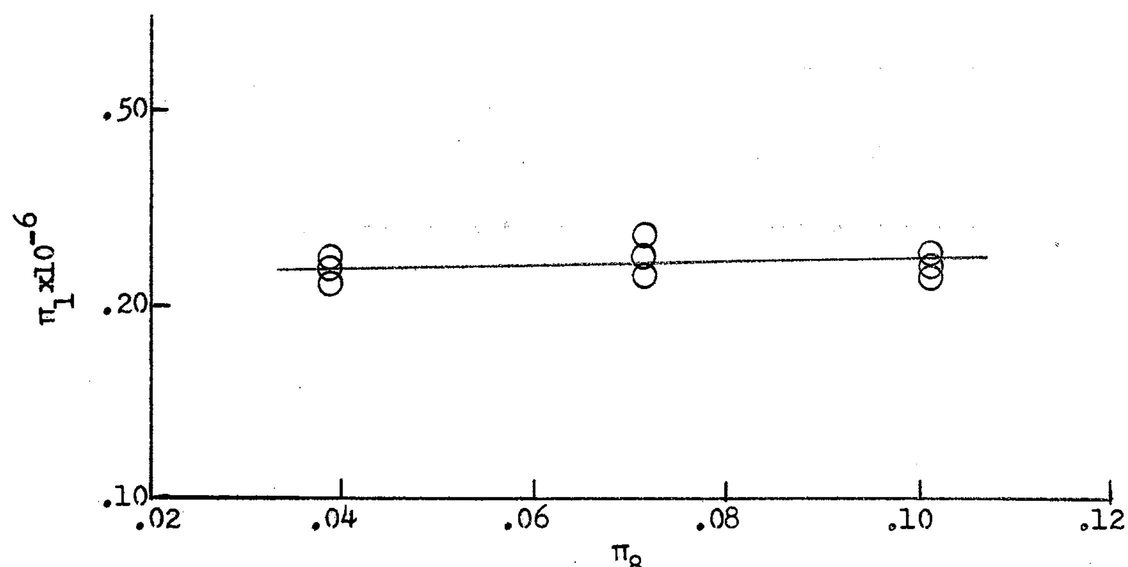

Figure 27. Plot of π_1 versus π_8. Film coverage at the downwind end of the reservoir. Velocity averaged 858 fpm.

TABLE XIII

RESULTS OF THE LINEAR REGRESSION ANALYSIS
COMPARING π_1 AND π_6

Average Free Stream Velocity (fpm)	T Calculated	T Tabulated	Rejected Null Hypothesis
	In Lee of Barrier Individual Tests		
611	-.783	12.706	No
857	.183	12.706	No
605	1.732	12.706	No
864	.028	12.706	No
618	.404	12.706	No
855	1.728	12.706	No
	Combined Data		
611	-.00557	2.365	No
859	.274	2.365	No
	Downwind End of Reservoir Individual Tests		
611	-2.491	12.706	No
857	-.604	12.706	No
605	-1.072	12.706	No
864	-1.518	12.706	No
618	-4.890	12.706	No
855	3.906	12.706	No
	Combined Data		
611	-1.144	2.365	No
859	.733	2.365	No

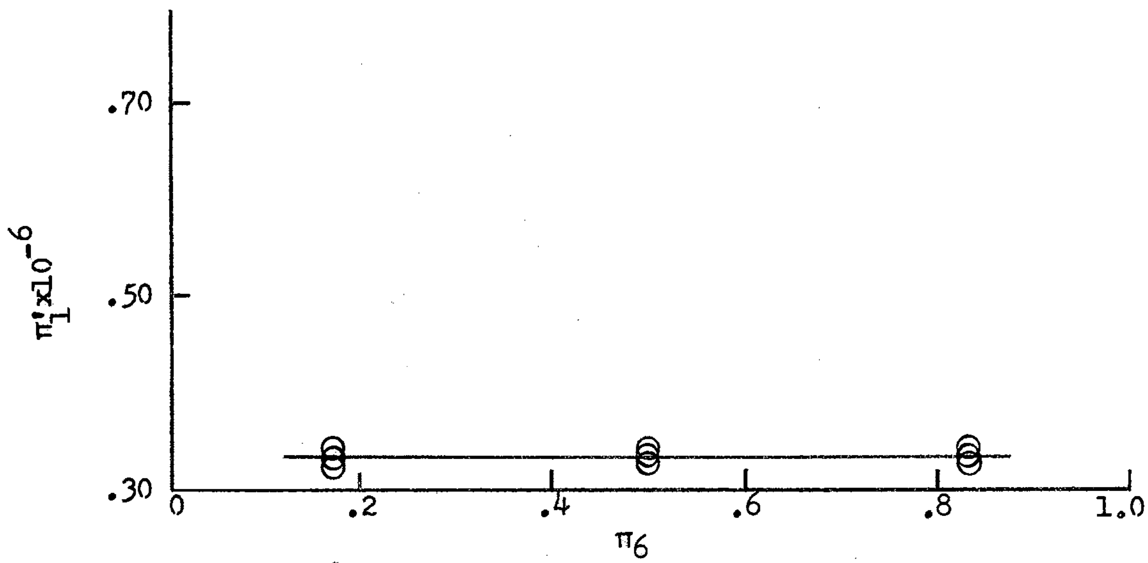

Figure 28. Plot of π_1' versus π_6 for film coverage in the lee of the barrier. Velocity averaged 611 fpm.

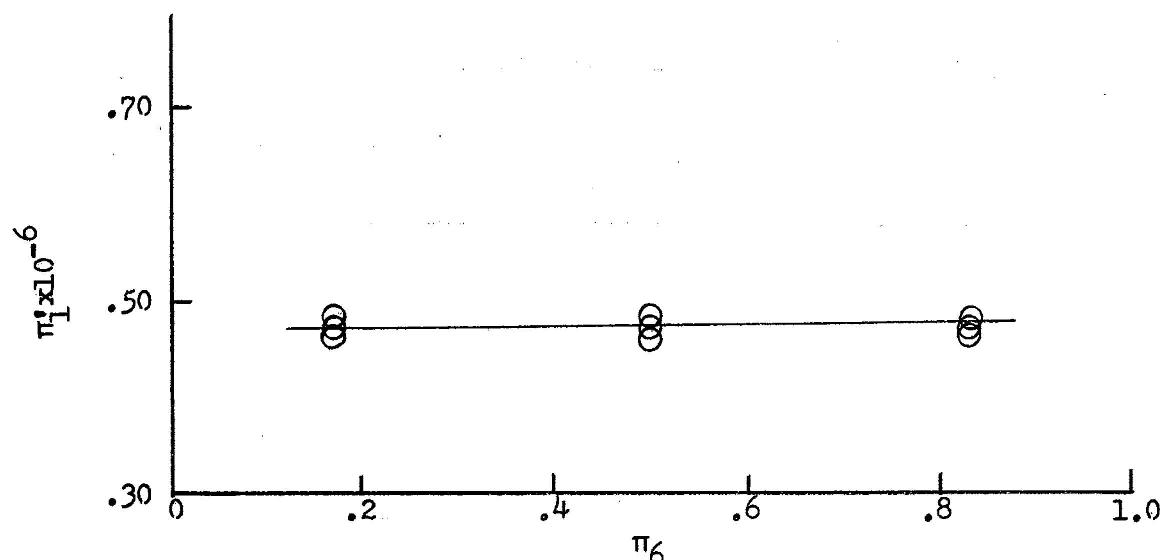

Figure 29. Plot of π_1' versus π_6 for film coverage in the lee of the barrier. Velocity averaged 859 fpm.

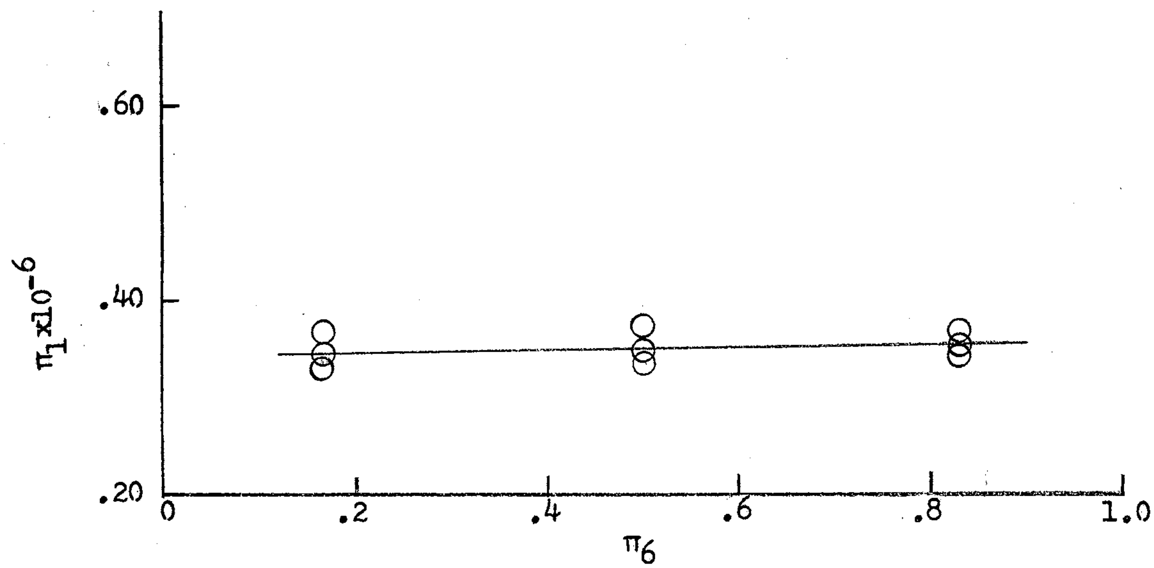

Figure 30. Plot of π_1 versus π_6. Film coverage at the downwind end of the reservoir. Velocity averaged 859 fpm.

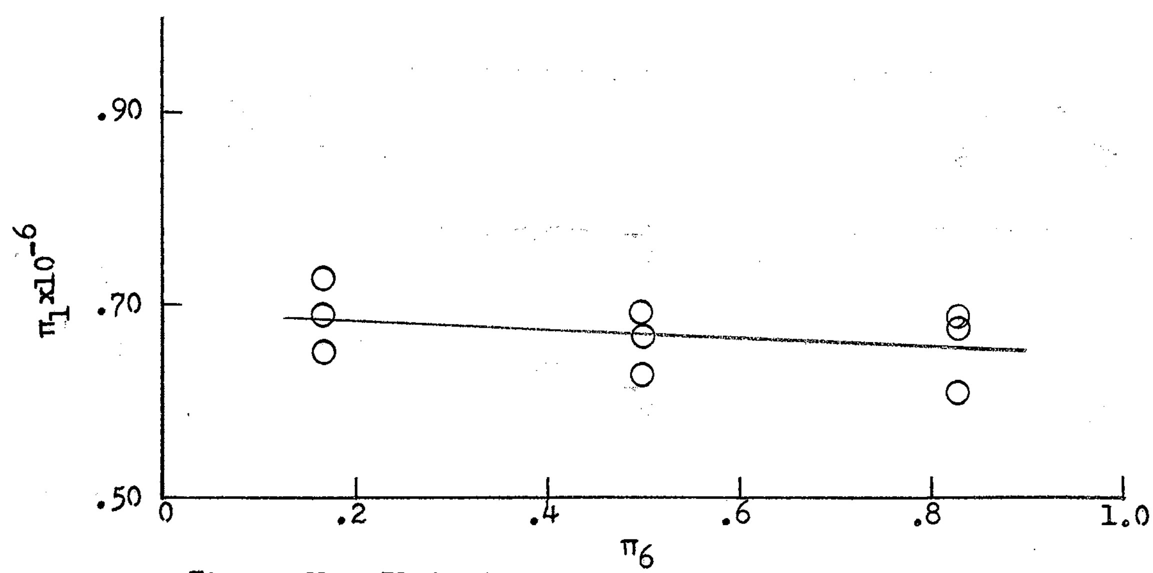

Figure 31. Plot of π_1 versus π_6. Film coverage at the downwind end of the reservoir. Velocity averaged 611 fpm.

TABLE XIV

RESULTS OF THE LINEAR REGRESSION ANALYSIS COMPARING π_1 AND π_7

Average Free Stream Velocity (fpm)	T Calculated	T Tabulated	Rejected Null Hypothesis
	In Lee of Barrier Individual Tests		
619	.743	12.706	No
860	.449	12.706	No
619	.873	12.706	No
851	.327	12.706	No
619	.309	12.706	No
860	.424	12.706	No
	Combined Data		
619	1.541	2.365	No
857	.966	2.365	No
	Downwind End of Reservoir Individual Tests		
619	-1.288	12.706	No
860	.901	12.706	No
619	.647	12.706	No
851	1.486	12.706	No
619	1.732	12.706	No
860	.180	12.706	No
	Combined Data		
619	-.968	2.365	No
857	-.257	2.365	No

concluded that the sloping barriers used in this study did not have a significant influence on the film coverage--either in the lee of the barrier or at the downwind end of the reservoir. Data are tabulated in Appendix A-7. Results of the regression analysis are plotted in Figures 32, 33, 34, and 35.

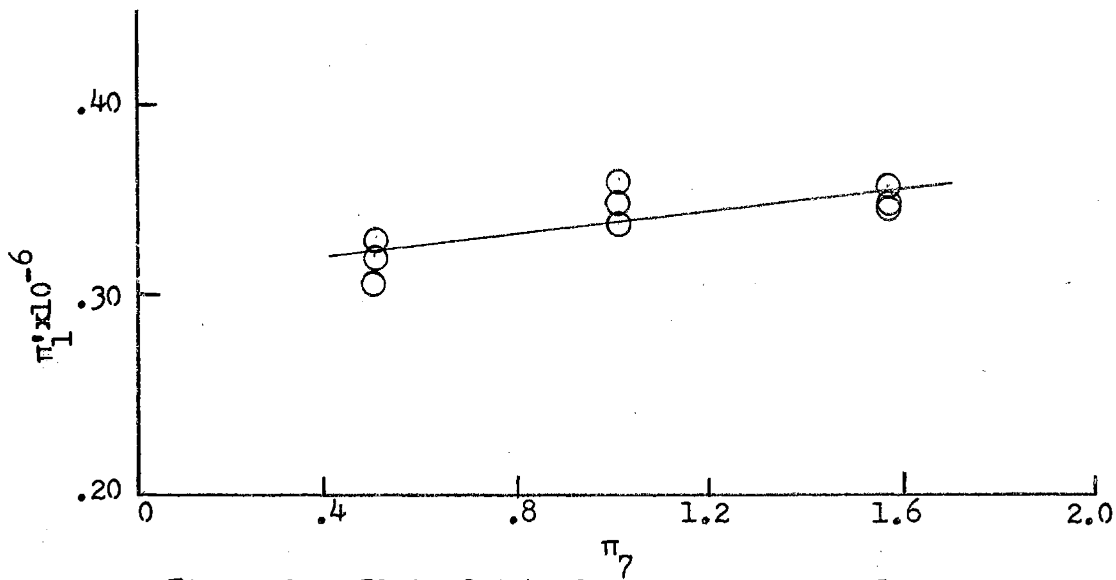

Figure 32. Plot of data for π_1' versus π_7. Film coverage in the lee of the barrier. Velocity averaged 619 fpm.

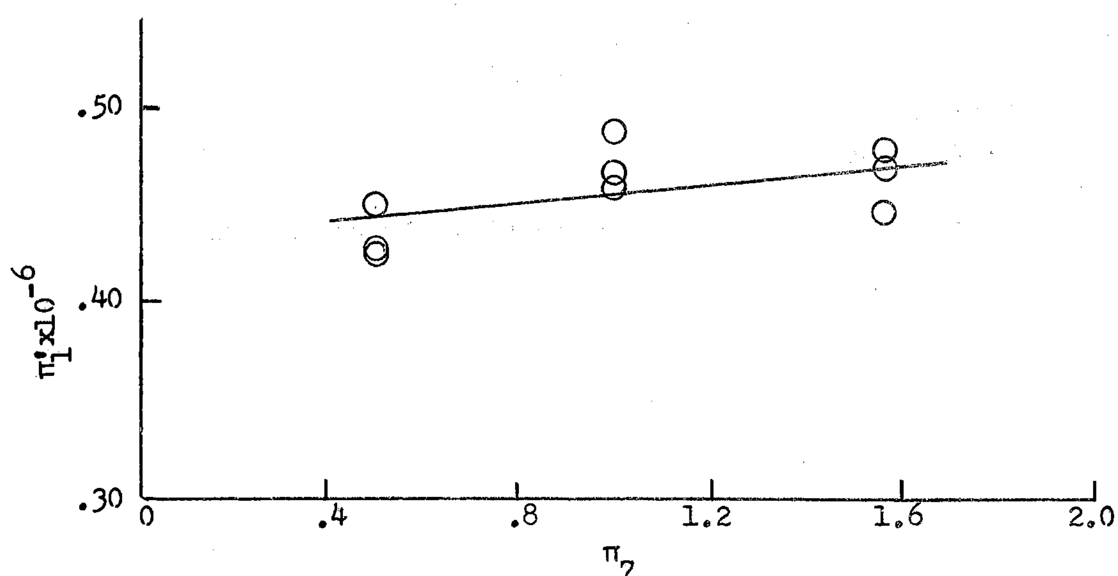

Figure 33. Plot of data for π_1' versus π_7. Film coverage in the lee of the barrier. Velocity 857 fpm.

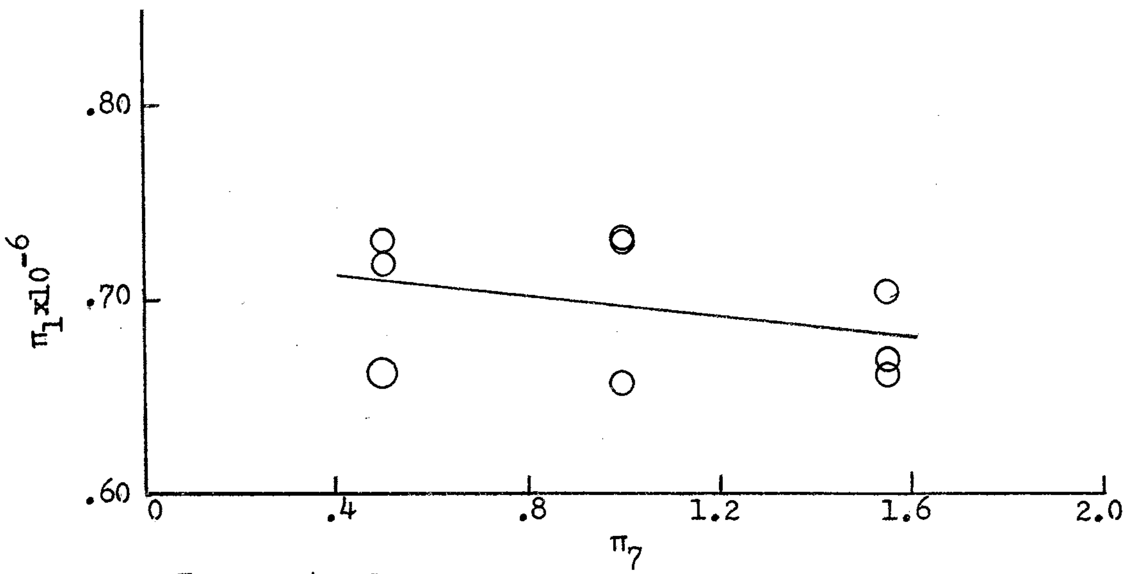

Figure 34. Plot of data for π_1 versus π_7. Film coverage at the downwind end of the reservoir. Velocity averaged 619 fpm.

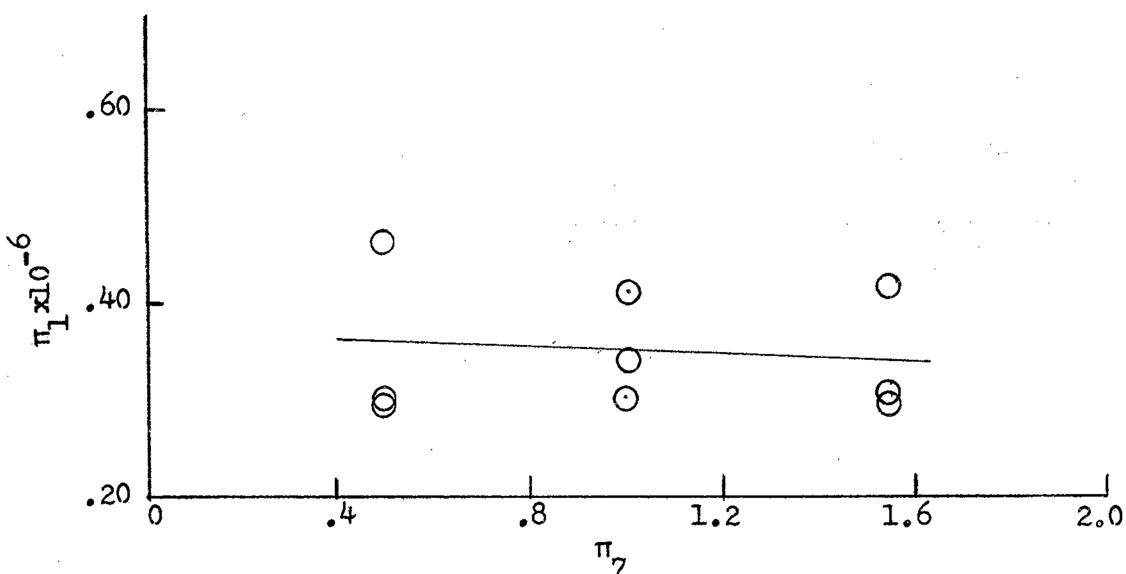

Figure 35. Plot of data for π_1 versus π_7. Film coverage at the downwind end of the reservoir. Velocity averaged 857 fpm.

CHAPTER VII

DISCUSSION

Unobstructed Air Flow

This was the first study of this kind known to the author and it was expected that some facets would not be investigated as thoroughly as needed. One limitation originally established was that no wave action would be permitted to develop. Instrumentation to measure wave height was not planned. In the final tests, some wave action did develop and undoubtedly introduced error.

Even though wave height was not measured, the most accurate prediction equation (6-2) gave good results. Comparison of observed and computed π_1 values showed a maximum difference of 18.4 percent. Over 65 percent of the differences were less than 5 percent. The simplified equation (6-4) resulted in a maximum of 21.9 percent difference in calculated and observed π_1 values. Over one-half the differences varied by less than 6 percent.

This comparison pointed out an advantage of the computer in analyzing the data. Many equations can be developed in a relatively short time and a comparison made to determine which equation was to be used. Comparing equations of different complexity enables the investigator to determine the improvement obtained in answers from several prediction equations.

There may be some problems in transferring results obtained in the laboratory study to the field. The investigation under controlled conditions did produce a prediction equation from which to start planning a field study.

Barrier Influence

Several useful facts were determined about barrier use. The most important was that the protected area in the lee of a barrier does not vary appreciably as wind velocity changes. This is in agreement with material presented by Woodruff and Geiger. One barrier design should be satisfactory for numerous wind conditions. The width of the barrier was not of significance. This permits construction of the barrier to meet structural requirements under many situations. Failure of sloping barriers to show advantage over vertical barriers relieves the planner of the need to design for unusual shapes. The fact that percentage of perforated area and location of perforations did not have significant effects, permits the use of some open area. As a result, the forces acting on the barrier would be reduced and less structural strength would be required. Additional studies to determine the maximum open area permissible should be conducted. Statements by Geiger (1965) indicated that this could be as much as 22 percent if proper distribution of the open area is determined.

Length of reservoir for this investigation was not sufficient to obtain data on which to predict the influence of a series of barriers. Results using six water bays showed some having open water areas while others had complete coverage. Barriers used were 1 inch high and placed every 4 feet. This is a phenomenon that may not be predictable because of the disturbing influence of numerous obstructions in the air stream. Each barrier may influence the air flow in a different manner that depends on the conditions influencing the air flow approaching the barrier under study.

CHAPTER VIII

SUMMARY AND CONCLUSIONS

Summary

Hexadecanol has shown promise as a water evaporation suppressing agent. Field investigations showed that maintaining film coverage over water with wind blowing was very difficult. The field studies were carried out under unsteady conditions, therefore, relationships between air velocity and film coverage were not established. Several field trials had been conducted using barriers to protect small areas of water from direct air flow and thus increase film coverage. The barrier studies were conducted under similar unsteady conditions.

The investigation reported in this dissertation was carried out in the laboratory where a wind tunnel provided more stable air velocities. It must be recognized that air temperature and barometric pressure were not controlled and the fan speeds fluctuated somewhat. True, steady state conditions were not developed, but the limits of variation were held to a relatively narrow range.

Air velocities were established by the facilities available. When no barriers were used, the minimum velocity was such that a measureable section of open water preceded the hexadecanol film. To obtain similar conditions with barriers in place, a higher velocity was required. Maximum velocity was determined by wave action developed. Water was not permitted to splash out of the reservoir when a test was being conducted.

Velocity measurements were made with a thermo-anemometer reading in feet per minute. Accuracy of the instrument was approximately ± 2 percent. Extent of film coverage was determined by visual observation. Micronized aluminum was spread on the film surface and gave the approximate location of the film edge. Light interference showed the exact edge of the film. Irregularities in the edge made precise measurement difficult. Film position was visually averaged and estimated to the nearest 0.1 foot.

The first set of experiments were carried out in the spring of 1964. Analysis of these data led to a refined experimental procedure. All data used in the analyses reported in this dissertation were obtained during the summer of 1965. Each experiment was repeated three times. This permitted a change in ambient conditions so a range of situations was encountered. Experiments were conducted to determine hexadecanol film coverage without barriers, with varied barrier heights, with barriers having varied amounts of open area, with barriers having perforations at three different elevations, with low, flat barriers, and with barriers sloping 30, 60, and 90 degrees from the horizontal.

Computer facilities were used to analyze all data. A multivariable regression program using the least squares method was used to evaluate film coverage when no barriers were present. Linear regression analyses were used to determine the several barrier influence relationships. In all cases, π_1 was the dependent variable.

Conclusions

1. The laboratory study produced a prediction equation using dimensionless ratios that permitted calculation of the film coverage under varying conditions. This equation is

$$\pi_1 = \frac{3.26 \times 10^4}{\pi_2^{.42}\ \pi_3^{.43}}$$

2. Analysis of data relating film coverage to other pertinent quantities resulted in another prediction equation that gave good results. The equation in this form is

$$XF = 1.45\text{x}10^{15}\ \frac{\tau^{1.09}\ Pc^{3.09}}{V^{2.38}}$$

3. Change in wind profile characteristics between 1 and 24 inches from the water surface did not significantly influence the extent of film coverage. Profiles used were $v = V(y/\Delta)^{.17}$ and $v = V(y/\Delta)^{.25}$.

4. Barrier height influenced the extent of film coverage in the lee of the barrier but did not significantly influence coverage at the downwind end of the reservoir when a single upwind barrier was used.

5. Barrier height influenced coverage at both ends of the reservoir when a barrier was placed at the upwind and downwind end of the reservoir.

6. The film coverage in the lee of the barrier was not appreciably influenced by air velocity for a particular barrier height.

7. Barrier width did not significantly influence film coverage when low, flat barriers were used.

8. The amount of perforated area and position of perforations did not significantly influence film coverage under the conditions set up in the laboratory.

9. Barrier slopes of 30, 60, and 90 degrees did not significantly influence film coverage.

Suggestions for Future Research

The length of the present reservoir set a relatively high velocity as the minimum that could be used. It would be well to extend the reservoir length so studies at lower air velocities could be carried out. Some modifications of the downwind end of the reservoir so water would not splash out of the reservoir would permit somewhat higher velocities to be used. As wave action will then become a significant factor, adequate equipment will be required to measure the wave effect. Reports by Geiger suggest that a larger percentage of open area may be permitted without detrimental effects. An extensive study on perforation size, placement, and total area could be very informative. The above items are suggestions for extending the laboratory investigations.

A similar field study should be conducted without using barriers and using vertical barriers. A major problem in the study without barriers will be selection of a location where approach conditions do not unduly influence the air flow pattern. This location will also present a major obstacle to adequate instrumentation.

One barrier study of interest is the use of barriers surrounding the entire reservoir and having a height approximately 1/12 that of the reservoir width. A second project of interest would be the use of low, narrow barriers--extending about 1/2 inch above the water--and forming a gridwork about 4 feet by 4 feet.

The first study would extend and refine the material presented in this dissertation while the outdoor studies would be used to relate actual conditions to laboratory investigations and would explore some types of barrier installations that have not been evaluated to date.

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APPENDIX A

EXPERIMENTAL DATA

APPENDIX A-1

VELOCITY DATA SIX INCHES UPWIND FROM THE RESERVOIR*

$$v = V(y/\Delta)^{.17}$$

Dist. From Floor (in.)	Mean Free Stream Vel.	Velocity (fpm) 10" From L. Wall	on Centerline	10" From Rt. Wall
1	256	140	136	134
2		163	150	163
3		187	174	187
6		203	201	196
9		223	221	221
12		237	230	234
18		254	250	250
24		268	254	247
1	630	335	341	355
2		395	388	415
3		428	469	428
6		509	515	495
9		536	549	536
12		556	569	542
18		589	609	609
24		609	656	629
1	925	549	515	529
2		623	616	609
3		723	723	670
6		770	763	743
9		804	837	804
12		844	877	837
18		911	904	877
24		924	924	938
1	595	341	368	348
2		388	402	402
3		435	442	448
6		495	480	489
9		522	549	529
12		536	562	562
18		576	589	576
24		582	603	609

*Three positions across the wind tunnel were used--one ten inches from the left wall, the second on the center line of the tunnel, and the third ten inches from the right wall.

APPENDIX A-1 (Continued)

Dist. From Floor (in.)	Mean Free Stream Vel.	Velocity (fpm) 10" From L. Wall	on Centerline	10" From Rt. Wall
1	1076	656	616	603
2		723	696	690
3		777	777	777
6		857	844	844
9		911	938	897
12		951	991	964
18		1045	1045	991
24		1072	1085	1072
1	1811	1072	1072	1058
2		1125	1179	1179
3		1139	1286	1273
6		1313	1474	1393
9		1407	1554	1527
12		1527	1661	1541
18		1661	1809	1608
24		1849	1876	1708
1	618	368	355	355
2		455	422	428
3		482	482	455
6		502	495	495
9		542	549	549
12		549	569	549
18		582	603	576
24		609	623	623
1	888	603	576	576
2		703	616	643
3		735	703	716
6		750	737	723
9		777	804	804
12		804	830	837
18		837	884	871
24		857	897	911
1	1814	1273	1179	1018
2		1407	1326	1206
3		1541	1407	1393
6		1440	1433	1407
9		1527	1554	1527
12		1574	1608	1541
18		1742	1708	1608
24		1876	1876	1701

APPENDIX A-2

VELOCITY DATA SIX INCHES UPWIND FROM THE RESERVOIR*

$$v = V(y/\Delta)^{.25}$$

Dist. From Floor (in.)	Mean Free Stream Vel.	Velocity (fpm) 10" From L. Wall	on Centerline	10" From Rt. Wall
1	605	294	294	288
2		314	308	294
3		348	381	328
6		469	442	462
9		536	509	509
12		515	542	522
18		582	556	576
24		589	616	609
1	1002	509	495	482
2		529	522	502
3		562	609	542
6		770	723	743
9		857	790	804
12		837	857	844
18		958	938	964
24		978	991	1038
1	1842	964	911	924
2		1005	991	991
3		1072	1206	1125
6		1474	1393	1393
9		1675	1567	1541
12		1608	1688	1688
18		1775	1809	1715
24		1809	1876	1842

*Three positions across the wind tunnel were used--one 10 inches from the left wall, the second on the centerline of the tunnel, and the third 10 inches from the right wall.

APPENDIX A-3

VELOCITY DATA ON THE CENTERLINE (HORIZONTAL) OF THE WIND TUNNEL*

Dist. From Floor (in.)	Mean Free Stream Vel.	Velocity (fpm)		
		Upwind End	12 foot Point	Downwind End
1	630	294	321	335
2		308	361	368
3		381	402	408
6		442	482	462
9		509	562	536
12		542	576	562
18		556	623	609
24		616	636	649
1	1024	495	589	690
2		522	670	723
3		609	737	804
6		723	804	844
9		790	897	911
12		857	924	991
18		938	1038	1038
24		991	1072	1058
1	1965	911	1098	1139
2		991	1152	1206
3		1206	1206	1340
6		1393	1433	1608
9		1567	1574	1688
12		1688	1715	1768
18		1809	1943	1956
24		1876	2010	2010

*At the upwind position, the 12 foot point and 6 inches upwind from the downwind end of the reservoir for $v = V(y/\Delta)^{.25}$ at the upwind end.

APPENDIX A-4

DATA USED TO DETERMINE EFFECT OF VELOCITY PROFILE ON FILM COVERAGE

$$v = V(y/\Delta)^{.17}$$

Air Temp. (°F)	Barometric Pressure (in.hg)	Free Stream Velocity (V) (fpm)	Film Coverage (ft)	Water Temperature (°F)
85.0	29.86	500	18.9	91.0
86.0	29.86	655	13.0	90.0
86.0	29.86	735	9.0	91.0
86.0	29.86	885	3.9	90.0
87.0	29.88	1105	2.2	89.8
76.0	30.22	490	20.2	90.0
76.0	30.22	655	13.8	90.0
76.2	30.22	735	9.4	90.2
76.2	30.22	875	5.4	90.0
76.2	30.22	1110	2.4	90.5
77.0	30.22	510	20.5	90.5
77.0	30.22	655	12.3	90.0
78.0	30.22	725	10.0	90.0
78.0	30.22	895	4.9	90.0
78.0	30.22	1100	2.4	89.9

APPENDIX A-5

DATA USED TO DETERMINE EFFECT OF VELOCITY PROFILE ON FILM COVERAGE

$$v = V(y/\Delta)^{.25}$$

Air Temp. (°F)	Barometric Pressure (in. hg)	Free Stream Velocity (V) (fpm)	Film Coverage (ft)	Water Temperature (°F)
92.5	30.12	510	20.9	90.5
92.5	30.12	610	15.4	90.0
92.5	30.12	710	11.1	90.1
92.0	30.12	810	9.2	90.0
92.0	30.12	910	6.0	89.8
92.0	30.12	1010	3.8	90.0
92.0	30.12	1110	2.8	90.0
94.0	30.18	510	21.3	90.1
94.0	30.18	610	15.7	90.1
94.0	30.18	710	11.1	90.5
94.0	30.16	810	8.9	90.0
94.0	30.16	910	5.9	90.0
94.0	30.16	1025	3.2	90.0
94.0	30.16	1110	2.5	89.9
95.0	30.16	515	21.2	90.0
95.0	30.16	610	14.8	89.5
95.0	30.16	710	11.0	90.0
95.0	30.16	810	8.5	90.0
95.0	30.16	910	5.6	90.0
95.0	30.16	1010	3.8	89.9
95.0	30.16	1110	2.5	89.8

APPENDIX A-6

DATA USED TO DETERMINE EFFECT OF BARRIER HEIGHT ON FILM COVERAGE

Air Temp. (°F)	Barometric Pressure (in. hg)	Free Stream Velocity (V) (fpm)	Film Coverage (ft)		Barrier Height (in.)	Water Temperature (°F)
			Upwind	Downwind		
88.0	29.82	615	1.9	11.1	2	90.0
88.0	29.84	610	3.7	11.3	4	90.0
87.5	29.84	605	5.5	11.5	6	89.5
86.5	29.86	855	1.9	4.1	2	89.8
86.5	29.86	845	2.1	3.9	4	90.3
85.0	29.86	855	4.2	4.2	6	89.9
74.5	29.93	615	1.8	12.1	2	90.0
74.5	29.95	605	4.1	11.2	4	89.5
76.0	29.96	605	5.5	11.1	6	90.3
77.0	29.96	855	1.8	3.8	2	91.5
77.0	29.96	850	4.0	3.9	4	90.0
77.0	29.96	865	5.5	4.1	6	89.8
80.0	29.93	850	1.9	3.9	2	90.2
80.0	29.93	855	4.0	3.8	4	90.2
80.0	29.93	855	5.6	4.1	6	90.0
81.5	29.93	625	2.0	11.0	2	90.0
81.0	29.93	605	4.0	10.7	4	90.8
81.0	29.93	615	5.7	9.9	6	90.8
83.5	30.16	615	2.2	10.8	2	89.5
83.5	30.16	625	4.4	11.0	4	90.0
84.0	30.16	615	5.7	12.9	6	89.8

APPENDIX A-6 (Continued)

Air Temp. (°F)	Barometric Pressure (in. hg)	Free Stream Velocity (V) (fpm)	Film Coverage (ft) Upwind	Downwind	Barrier Height (in.)	Water Temperature (°F)
85.5	30.16	675	2.2	10.4	2	90.1
83.5	30.16	675	4.4	10.4	4	90.0
84.0	30.16	675	5.8	11.0	6	89.5
85.5	30.16	735	2.4	8.1	2	90.0
84.0	30.16	735	4.1	9.3	4	89.8
84.0	30.16	735	5.8	8.9	6	90.1
85.5	30.16	795	2.3	7.4	2	89.5
84.0	30.16	795	4.0	7.5	4	90.0
85.5	30.16	795	5.8	7.7	6	90.0
86.0	30.16	860	2.2	4.9	2	89.5
84.0	30.16	860	4.2	4.6	4	90.1
85.5	30.16	860	5.7	4.7	6	89.5
84.0	30.16	610	2.1	12.3	2	90.1
85.0	30.16	625	4.2	11.1	4	89.7
87.0	30.16	630	5.4	11.9	6	89.4
84.0	30.16	675	2.1	11.3	2	89.8
85.0	30.16	685	4.3	10.8	4	89.9
87.0	30.16	675	5.6	10.5	6	89.9
84.0	30.16	735	2.3	8.7	2	90.0
85.0	30.16	735	4.2	9.0	4	90.0
87.0	30.16	735	5.6	9.2	6	90.2

APPENDIX A-6 (Continued)

Air Temp. (°F)	Barometric Pressure (in. hg)	Free Stream Velocity (V) (fpm)	Film Coverage (ft) Upwind	Film Coverage (ft) Downwind	Barrier Height (in.)	Water Temperature (°F)
84.0	30.16	795	2.4	6.6	2	90.0
85.0	30.16	795	4.1	7.5	4	90.0
87.0	30.16	805	5.7	7.6	6	90.0
84.0	30.16	860	2.3	4.9	2	90.0
85.0	30.16	865	4.1	4.3	4	89.8
87.0	30.16	865	5.7	5.3	6	90.0
85.0	30.14	615	2.3	12.4	2	90.1
86.0	30.14	615	4.3	11.3	4	90.0
87.0	30.14	625	5.6	12.6	6	90.0
85.0	30.14	675	2.3	11.0	2	90.0
86.0	30.14	675	4.2	11.0	4	89.9
87.0	30.14	675	5.6	10.9	6	90.1
85.0	30.14	735	2.2	9.3	2	89.7
87.0	30.14	735	4.1	9.2	4	89.6
87.0	30.14	735	5.6	8.8	6	89.5
85.0	30.14	800	2.3	6.5	2	89.5
87.0	30.14	800	4.0	7.0	4	90.0
87.0	30.14	800	5.6	7.1	6	89.7
86.0	30.14	860	2.2	3.8	2	89.0
87.0	30.14	860	4.1	4.3	4	90.0
87.0	30.14	860	5.6	4.6	6	89.9

APPENDIX A-7

DATA USED TO DETERMINE THE EFFECT OF SLOPING BARRIERS ON FILM COVERAGE

Air Temp. (°F)	Barometric Pressure (in. hg)	Free Stream Velocity (fpm)	Film Coverage (ft)		Barrier Height (in.)	Angle From Horiz.	Water Temperature (°F)
			Upwind	Downwind			
77.0	29.96	610	5.9	10.9	6	90	89.5
78.0	29.96	630	5.4	11.6	6	60	90.0
78.0	29.96	615	5.1	11.7	6	30	89.8
78.5	29.96	860	5.5	3.6	6	90	90.0
78.5	29.96	860	5.3	3.5	6	60	90.0
78.0	29.96	865	5.0	3.4	6	30	90.6
81.5	29.93	615	5.8	11.0	6	90	89.8
81.5	29.93	625	5.9	10.7	6	60	90.0
81.5	29.93	615	5.3	10.9	6	30	90.0
82.0	29.91	845	5.4	5.0	6	90	89.8
81.5	29.93	850	5.6	4.9	6	60	90.0
81.5	29.93	860	5.1	5.5	6	30	89.5
78.0	30.04	860	5.6	3.4	6	90	90.0
78.0	30.04	865	5.7	3.9	6	60	90.5
78.0	30.04	860	5.3	3.5	6	30	90.1
79.5	30.06	625	5.6	11.3	6	90	90.0
79.5	30.06	615	5.7	11.9	6	60	90.0
79.5	30.06	615	5.4	11.9	6	30	90.0

APPENDIX A-8

DATA USED TO DETERMINE THE EFFECT OF BARRIER WIDTH ON FILM COVERAGE

Air Temp. (°F)	Barometric Pressure (in. hg)	Free Stream Velocity (V) (fpm)	Film Coverage (ft)	Barrier Width (in.)	Water Temp. (°F)
95.0	30.16	860	7.7	.13	89.8
95.0	30.16	860	7.1	2.00	90.1
95.0	30.16	865	7.2	4.00	90.0
95.0	30.16	860	7.1	6.00	89.8
95.5	30.16	1105	3.8	.13	90.0
95.5	30.16	1105	3.7	2.00	89.5
95.0	30.16	1110	4.0	4.00	89.8
95.0	30.16	1110	4.5	6.00	89.5
94.5	30.10	845	8.3	.13	90.5
94.5	30.10	845	7.8	2.00	90.2
94.5	30.10	845	7.9	4.00	90.0
94.5	30.10	845	7.7	6.00	90.0
94.5	30.10	1110	3.4	.13	89.5
94.5	30.10	1110	3.5	2.00	89.9
94.5	30.10	1110	3.5	4.00	89.8
94.5	30.10	1110	3.3	6.00	90.0
93.5	30.11	860	7.6	.13	89.9
93.5	30.11	870	7.1	2.00	90.0
93.5	30.10	860	7.3	4.00	89.8
93.5	30.10	865	7.1	6.00	90.2
93.5	30.10	1105	3.7	.13	90.0
93.5	30.10	1110	3.7	2.00	90.2
93.5	30.10	1125	3.6	4.00	89.5
93.5	30.10	1120	3.7	6.00	89.8

APPENDIX A-9

DATA USED TO DETERMINE THE EFFECT OF SLIGHT PERFORATION ON FILM COVERAGE

Air Temp. (°F)	Barometric Pressure (in. hg)	Free Stream Velocity (V) (fpm)	Film Coverage (ft) Upwind	Film Coverage (ft) Downwind	Barrier Height (in.)	Percentage Of Area Perforated	Water Temperature (°F)
78.5	30.12	610	5.4	11.9	6	.0387	89.4
79.0	30.12	610	5.4	12.3	6	.0718	89.9
79.0	30.12	610	5.7	12.6	6	.1076	90.6
79.0	30.12	850	5.4	3.8	6	.0387	90.1
79.0	30.12	850	5.5	3.9	6	.0718	90.6
79.0	30.12	855	5.3	4.0	6	.1076	90.0
87.5	30.08	615	5.6	12.1	6	.0387	90.0
87.5	30.08	610	5.6	12.5	6	.0718	89.7
87.5	30.08	610	5.5	12.0	6	.1076	89.9
87.5	30.08	860	5.5	4.0	6	.1076	90.0
88.0	30.08	860	5.5	4.5	6	.0718	90.0
88.0	30.08	860	5.4	4.2	6	.0387	90.6
89.0	30.08	615	5.4	11.7	6	.0387	90.2
89.0	30.08	615	5.5	11.8	6	.0718	90.0
89.0	30.08	625	5.4	11.3	6	.1076	90.3
89.0	30.08	865	5.3	4.2	6	.1076	90.0
89.0	30.08	870	5.4	4.2	6	.0718	90.0
89.0	30.08	860	5.6	4.1	6	.0387	89.8

APPENDIX A-10

DATA USED TO DETERMINE THE EFFECT OF PERFORATION POSITION ON FILM COVERAGE

Air Temp. (°F)	Barometric Pressure (in. hg)	Free Stream Velocity (V) (fpm)	Film Coverage (ft)		Barrier Height (in.)	Distance From Floor (in.)	Water Temperature (°F)
			Upwind	Downwind			
76.5	30.23	610	5.5	11.9	6	1	90.0
76.5	30.23	615	5.5	11.1	6	3	90.5
76.5	30.23	610	5.4	11.1	6	5	90.0
79.0	30.23	850	5.5	4.3	6	1	90.0
79.0	30.23	865	5.6	4.3	6	3	90.0
79.5	30.24	860	5.5	4.2	6	5	90.0
76.0	29.96	610	5.4	11.3	6	1	90.0
76.0	29.96	605	5.5	11.0	6	3	91.0
76.0	29.96	605	5.5	11.1	6	5	91.0
76.5	29.96	870	5.5	3.9	6	1	89.5
76.5	29.96	865	5.4	4.0	6	3	90.1
77.0	29.96	860	5.6	4.0	6	5	89.8
81.0	29.93	860	5.4	3.9	6	1	89.4
81.0	29.93	860	5.4	4.0	6	3	89.5
81.5	29.93	850	5.5	4.3	6	5	90.0
83.0	29.93	615	5.6	10.7	6	1	91.5
83.0	29.93	615	5.5	10.3	6	3	90.2
83.0	29.93	625	5.6	10.0	6	5	90.0

APPENDIX A-11

DATA USED TO EVALUATE THE EFFECTS OF SUCCESSIVE BARRIERS ON FILM COVERAGE

Air Temp. (°F)	Barometric Pressure (in. hg)	Free Stream Velocity (V) (fpm)	Film Coverage (ft) Bay 1 Upwind	Bay 1 Downwind	Bay 2 Upwind	Bay 2 Downwind	Bay 3 Upwind	Bay 3 Downwind	Barrier Height (in.)	Water Temp. (°F)
100.0	30.03	1415	4.0	4.0	1.5	4.0	1.8	3.7	2	90.3
100.0	30.03	1515	4.0	4.0	1.5	3.3	1.7	3.0	2	90.0
100.0	30.03	1615	4.0	4.0	1.4	2.8	1.6	2.7	2	89.9
100.0	30.03	1715	4.0	4.0	1.4	2.3	1.6	2.2	2	89.7
100.0	30.03	1815	2.2	3.0	1.4	1.8	1.4	1.6	2	90.0
100.0	30.03	1920	2.0	2.6	1.3	1.5	1.3	1.2	2	90.0
99.8	30.02	1415	4.0	4.0	1.4	3.8	1.6	3.7	2	89.7
99.8	30.02	1515	4.0	4.0	1.3	3.1	1.5	2.9	2	89.9
99.8	30.02	1615	4.0	4.0	1.3	2.5	1.5	2.2	2	90.0
99.8	30.02	1715	2.1	3.3	1.3	2.3	1.4	2.0	2	90.1
99.8	30.02	1815	2.0	3.0	1.2	1.7	1.4	1.7	2	90.0
99.8	30.02	1920	2.0	2.3	1.1	1.4	1.3	1.4	2	89.0
84.5	30.08	1415	4.0	4.0	1.4	3.7	1.6	3.4	2	90.0
84.5	30.08	1515	4.0	4.0	1.4	2.8	1.5	2.6	2	89.5
84.5	30.08	1615	4.0	4.0	1.3	2.1	1.5	2.1	2	89.0
84.5	30.08	1715	2.0	3.4	1.3	1.9	1.5	1.8	2	89.0
84.5	30.08	1815	2.0	2.7	1.3	1.7	1.4	1.6	2	89.0
84.5	30.08	1920	1.8	2.4	1.2	1.3	1.5	1.3	2	89.0
88.0	30.08	1010	6.0	6.0	2.2	6.2			3	90.0
88.0	30.08	1110	6.0	6.0	2.4	5.4			3	90.0
88.0	30.08	1215	3.1	7.0	2.1	4.4			3	89.9
88.0	30.08	1315	3.1	5.2	2.1	3.6			3	90.0
88.0	30.08	1415	3.0	4.3	2.0	3.0			3	90.1
88.0	30.08	1515	3.1	3.3	2.0	2.6			3	90.0

APPENDIX A-11 (Continued)

Air Temp. (°F)	Barometric Pressure (in. hg)	Free Stream Velocity (V) (fpm)	Film Coverage (ft) Bay 1 Upwind	Bay 1 Downwind	Bay 2 Upwind	Bay 2 Downwind	Bay 3 Upwind	Bay 3 Downwind	Barrier Height (in.)	Water Temp. (°F)
89.0	30.08	1010	6.0	6.0	2.6	7.0			3	89.8
89.0	30.08	1110	6.0	6.0	2.3	5.7			3	90.0
89.0	30.08	1215	3.1	6.6	2.1	4.6			3	90.0
89.0	30.08	1315	3.1	5.2	2.1	3.6			3	90.0
89.0	30.08	1415	3.1	4.0	2.1	2.9			3	89.7
89.0	30.08	1515	3.0	3.2	2.1	2.4			3	89.5
98.0	30.05	805	5.7	9.9					6	89.6
98.0	30.05	910	5.7	7.6					6	90.0
98.0	30.05	1010	5.7	6.2					6	90.0
98.0	30.05	1110	5.6	4.6					6	90.0
98.0	30.05	1215	5.5	3.9					6	90.0
98.0	30.05	1315	5.5	3.5					6	90.0
98.0	30.05	1415	5.5	2.6					6	90.0
99.0	30.05	805	5.8	9.3					6	90.0
99.0	30.05	910	5.8	7.5					6	90.0
99.0	30.05	1010	5.8	5.6					6	90.0
99.0	30.05	1110	5.8	4.6					6	89.8
99.0	30.05	1215	5.7	3.7					6	89.7
99.0	30.05	1315	5.6	3.4					6	90.0
99.0	30.05	1405	5.6	2.9					6	90.0
100.0	30.05	810	5.8	9.7					6	89.8
100.0	30.05	910	5.8	7.6					6	89.9
100.0	30.05	1010	5.7	5.7					6	90.0
100.0	30.05	1110	5.7	4.6					6	90.0
100.0	30.05	1215	5.7	3.8					6	90.0
100.0	30.05	1315	5.6	3.2					6	89.8
100.0	30.05	1405	5.5	2.7					6	90.0

APPENDIX A-12

DATA USED TO EVALUATE EFFECT OF HEIGHT OF BARRIER ON FILM COVERAGE*

Air Temp. (°F)	Barometric Pressure (in. hg)	Free Stream Velocity (V) (fpm)	Film Coverage (ft) Upwind	Film Coverage (ft) Downwind	Barrier Height (in.)	Number of Barriers	Water Temperature (°F)
90.0	30.08	805	2.2	7.5	2	2	91.0
90.0	30.08	910	2.1	5.2	2	2	90.3
90.0	30.08	1010	2.1	3.8	2	2	90.2
90.0	30.08	1110	2.1	2.6	2	2	90.1
90.0	30.08	1215	2.0	1.8	2	2	90.0
90.0	30.08	1315	2.0	1.6	2	2	90.0
88.5	30.08	805	6.0	10.0	6	2	89.5
88.5	30.08	910	5.8	7.8	6	2	90.0
88.5	30.08	1010	5.8	6.2	6	2	90.2
88.5	30.08	1110	5.7	4.7	6	2	90.2
88.5	30.08	1215	5.6	3.8	6	2	90.1
88.5	30.08	1315	5.5	3.0	6	2	90.0
88.5	30.08	805	4.2	9.4	4	2	90.0
88.5	30.08	910	4.2	6.5	4	2	90.0
88.5	30.08	1010	4.1	5.1	4	2	89.9
88.5	30.08	1110	4.2	4.0	4	2	89.7
88.5	30.08	1215	4.1	3.2	4	2	90.0
88.5	30.08	1315	4.0	2.5	4	2	90.2

*One barrier at the upwind end and one barrier at the downwind end of the reservoir.

APPENDIX A-13

DATA FOR DETERMINATION OF WATER TEMPERATURE ON FILM COVERAGE

Air Temp. (°F)	Barometric Pressure (in. hg)	Free Stream Velocity (V) (fpm)	Film Coverage (ft)	Water Temperature (°F)
90.0	29.88	565	16.7	70.0
92.0	29.88	565	15.1	75.0
92.0	29.88	570	14.8	80.0
92.0	29.88	565	14.2	85.0
92.0	29.88	570	13.4	90.0
92.0	29.88	570	12.8	95.0
92.0	29.88	570	12.3	100.0
95.0	29.94	655	13.2	52.0
95.0	29.94	655	12.6	55.0
95.0	29.94	655	12.0	60.0
95.0	29.94	655	11.6	65.0
96.0	29.94	655	11.5	70.0
96.0	29.94	655	11.3	75.0
96.0	29.94	655	11.1	80.0
96.5	29.95	655	10.9	85.0
96.5	29.95	655	10.6	90.0
96.5	29.95	655	10.4	95.4
97.0	29.95	655	10.1	100.0
96.0	30.02	740	11.5	51.0
96.0	30.02	740	11.0	55.0
96.0	30.02	740	10.4	60.0
96.5	30.02	740	9.7	65.0
97.0	30.02	740	9.4	70.0
97.0	30.02	725	8.8	75.0
97.0	30.02	740	8.7	80.0
98.0	30.02	740	8.5	85.0
98.0	30.02	750	8.2	90.0
98.5	30.02	740	8.2	95.0
98.5	30.02	740	8.0	100.0
85.0	30.02	850	7.2	52.0
85.0	30.02	850	7.0	55.0
85.0	30.02	860	6.2	60.0
85.0	30.02	850	6.3	65.0
85.0	30.02	845	6.3	70.0
88.0	30.02	845	6.1	75.0
88.0	30.02	850	5.7	80.0
89.0	30.02	840	5.8	85.0
90.0	30.02	845	6.0	90.0
91.0	30.02	840	6.0	95.0
92.0	30.02	845	5.7	100.0

APPENDIX A-13 (Continued)

Air Temp. (°F)	Barometric Pressure (in. hg)	Free Stream Velocity (V) (fpm)	Film Coverage (ft)	Water Temperature (°F)
95.5	30.01	940	6.0	50.0
95.5	30.01	940	5.6	55.0
95.5	30.01	925	5.4	60.0
95.5	30.01	940	5.0	65.0
96.0	30.01	925	4.8	70.0
97.0	30.01	910	4.8	75.0
97.0	30.01	940	4.3	80.0
97.0	30.01	940	4.1	85.0
97.0	30.01	940	3.9	90.0
98.0	30.01	940	3.8	95.0
98.0	30.01	940	3.7	100.0

APPENDIX B

COMPUTER PROGRAMS

APPENDIX B-1

THIS PROGRAM WAS ORIGINALLY DEVELOPED BY PROFESSOR PORTERFIELD FOR USE ON THE IBM 1410. IT PERFORMS A MULTIVARIABLE REGRESSION ANALYSIS. THE PROGRAM WAS MODIFIED BY THE AUTHOR FOR USE ON THE IBM 1620

```
3400032007013600032007024902402011499400202402                          MONITOR
‡‡JOB                              SIGN LOG SHEET
‡‡FORX
C  C   CURVEFITSCHWIESOW
       DEFINE DISK (10,3000)
       DIMENSION A(15,16),M(14),X(15),B(15)
   49  FORMAT(2F15.4)
   50  FORMAT(I4,I3,6I2,I4,14I2)
   52  FORMAT(E14.8)
   54  FORMAT(20X,I3,10X,I3)
   55  FORMAT(3E16.8)
   57  FORMAT(1X,6E13.5)
   58  FORMAT(1X,4F15.4)
   59  FORMAT(1X,10I5,14I2)
   60  FORMAT(//30X,12HBUILT MATRIX/)
   61  FORMAT(//30X,18HTRANSFORMED MATRIX/)
   62  FORMAT(//30X,12HCOEFFICIENTS/)
   63  FORMAT(//4X,45HVARIANCE    REGRESSION            RSQ          R /)
   64  FORMAT(//9X,19HPLOTTING POINT DATA/)
   65  FORMAT(7X,50HY              YCOMP            DIFER            PERCENT,/)
   66  FORMAT(/30X,13HMODIFIED DATA/)
   67  FORMAT(////30X,18HCURVE FIT ANALYSIS/)
    5  IV=1
       SYSQ=0.0
       DO 25 I=1,15
       DO 25 J=1,16
25     A(I,J)=0.0                                                            25
       PUNCH67
       IN=0                                                                  30
       READ50,NUOB,NINVA,KA,KB,KC,KD,KP,KQ,KE,(M(L),L=1,14)
       PUNCH59,NUOB,NINVA,KA,KB,KC,KD,KP,KQ,KE,(M(L),L=1,14)
       GO TO  (360,80,80),KA
  360  L7=NUOB
       L8=L7+1
       READ52,((A(I,J),J=1,L8),I=1,L7)
       GO TO 390
   80  TA=NUOB
       IF(KB-0)1001,81,1001
 1001  PUNCH66
   81  L7=1
       DO 82 L=1,NINVA
   82  L7=L7+M(L)
       L8=L7+1
       X(1)=1.0
       GO TO 125
  110  GO TO 125
  125  IJK=NINVA+1
  127  IF(KP-1)90,1002,90
 1002  READ55,(B(L),L=1,IJK)
       RECORD(IV)(B(L),L=1,IJK)
       GO TO 129
   90  FETCH(IV)(B(L),L=1,IJK)
  129  GO TO (360,140,128),KA
  128  CONTINUE
       DO 130 I=1,IJK
  130  B(I)=LOGF(B(I))
  140  L1=0
       L2=0
```

APPENDIX B-1 (Continued)

```
      IN=IN+1
 142  L2=L2+1
      IF(L2-NINVA)1003,1003,215
 1003 L3=M(L2)
      L4=0
 144  L4=L4+1
      IF(L4-L3)146,146,142
 146  L1=L1+1
      L5=L1+1
      X(L5)=(B(L2))**(L4)
      GO TO 144
 215  X(L1+2)=B(IJK)
  240 IF(KB-0)1004,265,1004
 1004 LL=L5+1
      PUNCH57,(X(L),L=2,LL)
      GO TO 265
 160  IN=IN+1
      GO TO 240
 265  SYSQ=SYSQ+X(L8)*X(L8)
      DO 325 I=1,L7
      DO 325 J=1,L8
325   A(I,J)=A(I,J)+X(I)*X(J)
      IF(IN-NUOB)127,335,335
335   DO 345 L=2,L7
345   B(L)=A(L,L8)-(A(L,1)*A(1,L8))/TA
      B(1)=SYSQ-(A(1,L8)*A(1,L8))/TA
      GO TO 390
 390  L9=L7-1
      DO 30 K=1,L9
      LP=K+1
      LA=K
      DO 28 JJ=LP,L7
      IF(ABSF(A(JJ,K))-ABSF(A(LA,K)))28,1005,1005
 1005 LA=JJ
  28  CONTINUE
     IF(LA-LK)30,30,1006
 1006 DO29J=1,L8
      TEMP=A(K,J)
      A(K,J)=A(LA,J)
  29  A(LA,J)=TEMP
  30  CONTINUE
      IF(KC-0)1007,450,1007
 1007 PUNCH60
 430  PUNCH57,((A(I,J),J=1,L8),I=1,L7)
450   L1=0
455   L1=L1+1
      DO 485 I=L1,L7
      TEMP=A(I,L1)
      DO 485 J=L1,L8
      IF(TEMP)480,485,480
480   A(I,J)=A(I,J)/(TEMP)
485   CONTINUE
      L2=L1+1
      IF(A(L1,L1)-0.0)495,975,495
 975  DO 978 I=L2,L7
```

APPENDIX B-1 (Continued)

```
      IF(A(I,L1)-0.0)980,978,980
 978  CONTINUE
      GO TO 525
 980  DO 985 J=L1,L8
      TEMP=A(I,J)
      A(I,J)=A(L1,J)
      A(L1,J)=TEMP
 985  CONTINUE
      PUNCH54,I,J
 495  DO 520 I=L2,L7
      TEMP=A(I,L1)
      DO 520 J=L1,L8
      IF(TEMP-0.0)515,520,515
515   A(I,J)=A(L1,J)-A(I,J)
520   CONTINUE
 525  IF(L1-L7+1)455,1008,1008
 1008 IF(A(L7,L7)-0.0)545,535,545
535   A(L7,L8)=0.0
      GO TO 555
545   A(L7,L8)=A(L7,L8)/A(L7,L7)
      A(L7,L7)=1.0
  555 IF(KD-0)1009,602,1009
 1009 PUNCH61
      PUNCH57,((A(I,J),J=1,L8),I=1,L7)
602   X(L7)=A(L7,L8)
      DO 630 I=2,L7
      N2=L8-I
      X(N2)=A(N2,L8)
      L1=I-1
      DO 630 J=I,L1
      N3=L8-J
      X(N2)=X(N2)-A(N2,N3)*X(N3)
630   CONTINUE
      PUNCH62
      PUNCH57,(X(I),I=1,L7)
      IF(KA-2)5,680,680
680   REGRE=0.0
      DO 690 I=2,L7
690   REGRE=REGRE+X(I)*B(I)
      RSQ=REGRE/B(1)
      R=RSQ**0.5
      PUNCH63
      PUNCH57,B(1),REGRE,RSQ,R
      IF(KE-0)1010,5,1010
 1010 IV=1
      GO TO (5,740,740),KA
740   LC1=0
      PUNCH64
      PUNCH65
  745 IF(KQ-I)986,1011,986
 1011 READ55,(B(I),I=1,IJK)
      GO TO 987
 986  FETCH(IV)(B(I),I=1,IJK)
  987 PUNCH57,(B(J),J=1,NINVA)
      LC1=LC1+1
```

APPENDIX B-1 (Continued)

```
      GO TO (5,750,880),KA
 880  J=1
      YCOMP=X(1)
      DO 881 I=1,NINVA
      IF(M(I)-1)881,1012,881
 1012 J=J+1
      B(I)=LOGF(B(I))
      YCOMP=YCOMP+X(J)*B(I)
 881  CONTINUE
      YCOMP=EXPF(YCOMP)
      GO TO 830
 750  LC2=1
      DO 805 J=1,NINVA                                          775
      IF(M(J)-0)1013,805,1013
 1013 LC3=M(J)
      DO 805 K=1,LC3                                            785
      LC2=LC2+1                                                 790
      A(1,LC2)=B(J)**K
 805  CONTINUE
      YCOMP=X(1)                                                810
      DO 825 I=2,L7                                             815
825   YCOMP=YCOMP+X(I)*A(1,I)                                   825
 830  CONTINUE
      IF(B(IJK)-0.0)850,1014,850
 1014 DIFER=0.0
      PERC=0.0
      GO TO 860
 850  DIFER=B(IJK)-YCOMP
      PERC=(DIFER/B(IJK))*100.0
 860  PUNCH58,B(IJK),YCOMP,DIFER,PERC
      IF(LC1-KE)745,1015,1015
 1015 GOTO5
      END
```

APPENDIX B-2

THIS PROGRAM WAS DEVELOPED FOR USE ON THE IBM 1410 AND IS TYPICAL OF ALL PROGRAMS USED TO PERFORM THE LINEAR REGRESSION ANALYSES. STATEMENTS APPROPRIATE TO THE PARTICULAR DATA WERE SUBSTITUTED TO CALCULATE THE CORRECT PI TERMS

```
MON$$     JOB  731140001       SCHWIESOW  PERFVARY
MON$$     ASGN MGO,A2
MON$$     ASGN MJB,A3
MON$$     MODE GO,TEST
MON$$     EXEQ FORTRAN,,,,,,,MAINPROG
      DIMENSION TFA(9),BARO(9),VEL(9),XFU1(9),XFD1(9),PI1U(9),PI1D(9)
      DIMENSION P(9),XFT1(9),PC(9),RHO(9),V(9),PI1T(9),XX(9),YY(9)
      DIMENSION TF(9),H(9),PI6(9)
      DIMENSION TC(10),TCA(10),AMU(10)
   83 FORMAT (F4.0,F6.1,F5.0,2F5.1,10X,F4.1,F7.4,F6.1)
  152 FORMAT(4X,3HVEL,5X,1HV,8X,4HPI1U,11X,4HPI1D,11X,4HPI1T,12X,3HPI6,
     112X,2HPC,11X,1HP,5X,1HH)
  163 FORMAT (F8.1,F7.1,5E15.6,F9.5,F6.1)
 300  FORMAT(4X,7HSLOPE =,E16.8,4X,8HUSLOPE =,E16.8,4X,8HBSLOPE =,E16.8)
 400  FORMAT(4X,7HYINTC =,E16.8,4X,3HR =,E16.8,4X,3HT =,E16.8,4X,4HSY =,
     1E16.8)
  404 FORMAT (4X,7HSQUAY =,E15.8,4X,7HSQUAX =,E15.8,4X,7HSQUXY =,E15.8)
  405 FORMAT (4X,6HSUMX =,E15.8,4X,7HSUMXA =,E15.8,4X,6HSUMY =,E15.8,4X,
     17HSUMYA =,E15.8)
  450 FORMAT (4X,5HSYY =,E16.8,4X,5HSXX =,E16.8,4X,5HSXY =,E16.8)
  451 FORMAT (80X)
      READ(1,83)(TFA(I),BARO(I),VEL(I),XFU1(I),XFD1(I),H(I),P(I),TF(I),
     1I=1,N)
      M=0
      XFT1(I)=XFU1(I)+XFD1(I)
      PI1U(I)=(XFU1(I)*RHO(I)*V(I))/AMU(I)
      PI1D(I)=(XFD1(I)*RHO(I)*V(I))/AMU(I)
      PI1T(I)=(XFT1(I)*RHO(I)*V(I))/AMU(I)
      PI6(I)=P(I)
      WRITE(3,152)
      WRITE(3,163)(VEL(K),V(K),PI1U(K),PI1D(K),PI1T(K),PI6(K),PC(K),P(K)
     1,H(K),K=1,N)
      DO 30 I=1,N
      YY(I)=PI1U(I)
      XX(I)=PI6(I)
   30 CONTINUE
      GO TO 100
   20 DO 31 I=1,N
      YY(I)=PI1D(I)
      XX(I)=PI6(I)
   31 CONTINUE
      GO TO 100
   35 DO 100 I=1,N
      YY(I)=PI1T(I)
      XX(I)=PI6(I)
  100 CONTINUE
      SUMX=0.0
      SUMY=0.0
      SQUXY=0.0
      SQUAX=0.0
      SQUAY=0.0
      B=N
      DO 200 I=1,N
      X=(XX(I))
      Y=(YY(I))
      SUMX=X+SUMX
      SUMY=Y+SUMY
      SQUAX=(X*X)+SQUAX
```

APPENDIX B-2 (Continued)

```
      SQUAY=(Y*Y)+SQUAY
      SQUXY=(X*Y)+SQUXY
  200 CONTINUE
      SUMXA=SUMX/B
      SUMYA=SUMY/B
      SUMXX = SUMX*SUMX
      SUMYY = SUMY*SUMY
      SUMXY=SUMX*SUMY
      SYY=SQUAY-(SUMYY/B)
      SXX=SQUAX-(SUMXX/B)
      SXY=SQUXY-(SUMXY/B)
      Q=(SXY*SXY)/SXX
      SLOPE=SXY/SXX
      S2Y=(SYY-Q)/(B-2.)
      SY=SQRT(S2Y)
      S2B1=S2Y/SXX
      SB1=SQRT(S2B1)
      USLOPE=SLOPE+(SB1*TN2)
      BSLOPE=SLOPE-(SB1*TN2)
      YINTC=(SUMY-(SLOPE*SUMX))/B
      R=SXY/(SQRT(SXX*SYY))
      T=SLOPE/SB1
      WRITE (3,300) SLOPE,USLOPE,BSLOPE
      WRITE (3,400) YINTC,R,T,SY
      WRITE(3,404) SQUAY,SQUAX,SQUXY
      WRITE(3,405) SUMX,SUMXA,SUMY,SUMYA
      WRITE(3,450) SYY,SXX,SXY
      DO 91 J=1,3
   91 WRITE(3,451)
      M=M+1
      GO TO (20,35,15),M
      END
     MON$$      EXEQ LINKLOAD
                PHASEONE
                CALL MAINPROG
     MON$$      EXEQ ONE,MJB
```

APPENDIX B-3

THIS PROGRAM WAS DEVELOPED FOR USE ON THE IBM 1620 TO PERFORM THE LINEAR REGRESSION ANALYSIS FOR VARIED ANGLES

```
34000320070136000320070249011O2 F0340020000100                         FORGO
C  C   ANGLESVARIED''SCHWIESOW
       DIMENSION H(9),PI1U(9),PI1D(9),PI1T(9),PC(9)
       DIMENSION TFA(9),BARO(9),VEL(9),XFU1(9),XFD1(9),XT(9),A(9),TF(9)
       DIMENSION XX(9),YY(9),XFT1(9),RHO(9),V(9),PI4(9)
       DIMENSION TC(10),TCA(10),AMU(10)
   10 FORMAT (I3,F10.4)
    5 FORMAT (F4.0,F6.2,F5.0,2F5.1,5X,2F5.1,F4.1,F6.1)
  152 FORMAT( 1X,3HVEL,5X,1HV,8X,4HPI1U,11X,4HPI1D,10X,3HPI4,12X,2HPC,
     15X,1HH)
  162 FORMAT( F6.0,F5.1,4E14.7,F4.0)
  300 FORMAT(1X,6HSLOPE=,E14.7,4X,7HUSLOPE=,E14.7,4X,8HBSLOPE=,E14.7)
  400 FORMAT(1X,7HYINTC=,E16.8,4X,3HR=,E16.8)
  401 FORMAT( 1X,3HT =,E16.8,4X,4HSY =,E16.8)
  404 FORMAT (1X,7HSQUAY =,E14.7,4X,7HSQUAX =,E14.7,4X,7HSQUXY =,E14.7)
  405 FORMAT(1X, 6HSUMX=,E15.8,4X,7HSUMXA=,E15.8)
  406 FORMAT( 1X,6HSUMY =,E15.8,4X,7HSUMYA =,E15.8)
  450 FORMAT (1X,5HSYY =,E16.8,4X,5HSXX =,E16.8,4X,5HSXY =,E16.8)
  451 FORMAT (80X)
      D=5./9.
      C=120.
      RHOO=2.378E-03
      AMUO=170.9E-06
      AMUE=AMUO/478.7
      TO=273.16
   15 READ 10, N,IN2
      READ 5,(TFA(I),BARO(I),VEL(I),XFU1(I),XFD1(I),XT(I),H(I),A(I),
     1TF(I),I=1,N)
      M=0
      DO 90 I=1,N
      XFT1(I)=XFU1(I)+XFD1(I)
      TC(I)=(TFA(I)-32.)*D
      TCA(I)=TC(I)+TO
      AMU(I)=AMUE*((TO+C)/(TCA(I)+C))*((TCA(I)/TO)**1.5)
      RHO(I)=RHOO*(BARO(I)/(TFA(I)+459.4))*17.32
      VEL(I)=VEL(I)*(630./470.)
      V(I)=VEL(I)/60.
      PC(I)=(53.0-((1./9.)*(TF(I)-41.)))*.0000685
      PI1U(I)=(XFU1(I)*RHO(I)*V(I))/AMU(I)
      PI1D(I)=(XFD1(I)*RHO(I)*V(I))/AMU(I)
      PI4(I)=A(I)/57.296
   90 CONTINUE
      PUNCH 152
      PUNCH 162,(VEL(K),V(K),PI1U(K),PI1D(K),PI4(K),PC(K),H(K),K=1,N)
      DO 30 I=1,N
      YY(I)=PI1U(I)
      XX(I)=PI4(I)
   30 CONTINUE
      GO TO 100
   20 DO 31 I=1,N
      YY(I)=PI1D(I)
      XX(I)=PI4(I)
   31 CONTINUE
      GO TO 100
  100 CONTINUE
      SUMX=0.0
      SUMY=0.0
      SQUXY=0.0
```

APPENDIX B-3 (Continued)

```
      SQUAX=0.0
      SQUAY=0.0
      B=N
      DO 200 I=1,N
      Y=(YY(I))
      X=(XX(I))
      SUMX=X+SUMX
      SUMY=Y+SUMY
      SQUAX=(X*X)+SQUAX
      SQUAY=(Y*Y)+SQUAY
      SQUXY=(X*Y)+SQUXY
  200 CONTINUE
      SUMXA=SUMX/B
      SUMYA=SUMY/B
      SUMXX = SUMX*SUMX
      SUMYY = SUMY*SUMY
      SUMXY=SUMX*SUMY
      SYY=SQUAY-(SUMYY/B)
      SXX=SQUAX-(SUMXX/B)
      SXY=SQUXY-(SUMXY/B)
      Q=(SXY*SXY)/SXX
      SLOPE=SXY/SXX
      S2Y=(SYY-Q)/(B-2.)
      SY=SQRTF(ABSF(S2Y))
      S2B1=S2Y/SXX
      SB1=SQRTF(ABSF(S2B1))
      USLOP=SLOPE+(SB1*TN2)
      BSLOP=SLOPE-(SB1*TN2)
      YINTC=(SUMY-(SLOPE*SUMX))/B
      R=SXY/(SQRTF(ABSF(SXX*SYY)))
      T=SLOPE/SB1
      PUNCH 300,SLOPE,USLOP,BSLOP
      PUNCH 400, YINTC,R
      PUNCH 401, T,SY
      PUNCH 404, SQUAY,SQUAX,SQUXY
      PUNCH 405, SUMX,SUMXA
      PUNCH 406, SUMY,SUMYA
      PUNCH 450, SYY,SXX,SXY
      DO 91 J=1,3
   91 PUNCH 451
      M=M+1
      GO TO(20,15),M
      STOP
      END
```

APPENDIX B-4

THIS PROGRAM WAS DEVELOPED FOR THE IBM 7040. IT PERFORMS A LINEAR REGRESSION ANALYSIS WHEN DATA IS READ IN AN X, Y, SEQUENCE

```
$JOB
$IBJOB          NODECK
$IBFTC          NODECK
      DIMENSION XX(99),YY(99)
   10 FORMAT (I3,F10.4)
   80 FORMAT (10F8.1)
  150 FORMAT (2F15.4)
 300  FORMAT(4X,7HSLOPE =,E16.8,4X,8HUSLOPE =,E16.8,4X,8HBSLOPE =,E16.8)
 400  FORMAT(4X,7HYINTC =,E16.8,4X,3HR =,E16.8,4X,3HT =,E16.8,4X,4HSY =,
     1E16.8)
  404 FORMAT (4X,7HSQUAY =,E15.8,4X,7HSQUAX =,E15.8,4X,7HSQUXY =,E15.8)
  405 FORMAT (4X,6HSUMX =,E15.8,4X,7HSUMXA =,E15.8,4X,6HSUMY =,E15.8,4X,
     17HSUMYA =,E15.8)
  450 FORMAT (4X,5HSYY =,E16.8,4X,5HSXX =,E16.8,4X,5HSXY =,E16.8)
  451 FORMAT (80X)
 15   READ 10,N,TN2
      READ 80,(XX(I),YY(I),I=1,N)
      SUMX=0.0
      SUMY=0.0
      SQUXY=0.0
      SQUAX=0.0
      SQUAY=0.0
      B=N
      DO 200 I=1,N
      X=XX(I)
      Y=YY(I)
      SUMX=X+SUMX
      SUMY=Y+SUMY
      SQUAX=(X*X)+SQUAX
      SQUAY=(Y*Y)+SQUAY
      SQUXY=(X*Y)+SQUXY
  200 CONTINUE
      SUMXA=SUMX/B
      SUMYA=SUMY/B
      SUMXX = SUMX*SUMX
      SUMYY = SUMY*SUMY
      SUMXY=SUMX*SUMY
      SYY=SQUAY-(SUMYY/B)
      SXX=SQUAX-(SUMXX/B)
      SXY=SQUXY-(SUMXY/B)
      Q=(SXY*SXY)/SXX
      SLOPE=SXY/SXX
      S2Y=(SYY-Q)/(B-2.)
      SY=SQRT(S2Y)
      S2B1=S2Y/SXX
      SB1=SQRT(S2B1)
      USLOPE=SLOPE+(SB1*TN2)
      BSLOPE=SLOPE-(SB1*TN2)
      YINTC=(SUMY-(SLOPE*SUMX))/B
      R=SXY/(SQRT(SXX*SYY))
      T=SLOPE/SB1
      PRINT 150,(XX(K),YY(K),K=1,N)
      PRINT 300,SLOPE,USLOPE, BSLOPE
      PRINT 400,YINTC,R,T,SY
      PRINT 404,SQUAY,SQUAX,SQUXY
      PRINT 405,SUMX,SUMXA,SUMY,SUMYA
      PRINT 450,SYY,SXX,SXY
      DO 91 J=1,3
 91   PRINT 451
      GO TO 15
      END
```

VITA

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