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SOLAR REFLECTANCE OF MONOLAYER COVERED AND CLEAN WATER SURFACES

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16. ABSTRACT

Monomolecular films, acting as diffusion barriers and simultaneously altering the reflective properties of water surfaces, can reduce evaporation. Analytical and experimental studies were made of the radiant energy input to untreated and monolayer-covered water surfaces. Values of direct solar radiation and energy absorbed by a water surface were computed and tabulated for different zenith distances, atmospheric pressures, and moisture and dust contents of the atmosphere. Values for solar energy input to a smooth water surface were computed and tabulated for latitudes of 30, 35, and 40 deg, at elevations of 1000 and 5000 ft, and precipitable atmospheric moisture values of 10, 20, 30, and 40 mm on 8 typical days throughout the year. Procedures for using these tabulations in the energy budget of water bodies are suggested. To estimate daily evaporation rates from water surfaces, an analytical model was developed to apply transient conditions to an element of a typical water reservoir covered by hypothetical films having different optical properties. Evaporation was reduced by 21% for a cetyl-alcohol monolayer and 36% for a highly reflective monolayer with diffusion properties of cetyl alcohol. A search was made to find film-forming materials with good diffusion barrier properties that would simultaneously increase solar energy reflectance. Yellow dyes were studied in an attempt to color a monolayer, since yellow reflects at wave lengths where solar energy has its peak intensity. Has 43 references.

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FOREWORD

During the several years that the Bureau of Reclamation conducted laboratory and field investigations of monomolecular films as evaporation retardants the complex nature of the overall problem became increasingly apparent. Many individual problems to be overcome were apparent from the beginning, and the tasks of solution were undertaken immediately, both inhouse and through a program of sponsored research. The early investigations were concerned, for the most part, with the more obvious engineering problems of applying monolayer forming materials to large water surfaces, the effects of the materials on wildlife and the environment, and the economic aspects of conserving water by this method.

Solutions to these problems, with the exception of monolayer maintenance under adverse wind conditions, were attained with relative ease. Evaluation of evaporation savings achieved by use of the monomolecular films and attempts to improve their efficiency brought to light many additional problems of a more fundamental nature that also required solution. Only a portion of these were investigated before the program was ultimately discontinued because of the apparent marginal benefits to be gained within the foreseeable future.

The overall program of investigations was developed and largely financed by the Bureau of Reclamation with some support to sponsored research coming from various State Water Resources Research Centers in the later years.

Among the investigations that were considered to be basic to precise evaluation of evaporation savings achieved through use of monomolecular films and the ultimate economic evaluation of their use as an operational procedure were:

(a) A better understanding of the process of heat and water vapor transfer across the air-water interface
(b) The effects of waves on evaporation from free water surfaces
(c) The contribution of spray to total water transport from water surfaces
(d) Evaluation of the influence of monomolecular films on wave shape and radiant properties of a water surface
(e) The relationship of solar-reflectance of monolayer-covered water surfaces and evaporation rates
(f) Development of instrumentation and techniques for direct measurement of water vapor flux to minimize the dependence on or eliminate the need for the very cumbersome energy budget, water budget, and aerodynamic methods for computing evaporation savings.

Item (a) was in the process of investigation at the time the program was discontinued. The study was designed to investigate the structure of the air and water laminar layers and to identify the mechanisms within these layers that affect the rate of evaporation and heat transfer. With improved instrumentation now available these studies were beginning to reveal facts contrary to reasonable expectations based on past observations and measurements. It seems reasonable to expect that explanations for apparent anomalies in the past observations might soon have been forthcoming.

Items (b) and (c) were the subjects of investigations which showed that waves on a water surface have a significant effect on the evaporation rate from that surface. Easterbrook at Cornell Aeronautical Laboratory was able to show a very definite relationship between surface wave conditions and evaporation rates with evaporation being reduced somewhat under certain wave conditions that suppress air turbulence. Beard, on the other hand, has shown analytically that the suppressed wave action resulting from monolayer applications gives a higher energy reflectance with corresponding decreases in evaporation rates. With regard to the contribution

of spray to total evaporation, Easterbrook's work indicated a negligible amount at wind speeds below 20 miles per hour (mph) but significant amounts at speeds above 30 mph.

Items (d) and (e) are in essence the subject matter of this report and are of fundamental value, particularly with regard to the energy budget method for determining evaporation savings and losses from large bodies of water. Use of the energy budget method for making these determinations requires extensive instrumentation and results in voluminous amounts of data. Analysis of the data is quite laborious, and the justification for use of the energy budget is that it is probably the most accurate approach to these evaluations. The work of Beard et. al. reported herein provides tabulated values and suggests procedures for their use in the energy budget procedure that should prove useful and time saving for anyone faced with such computations.

Development of instrumentation and techniques for measuring atmospheric water vapor and vapor flux was in an embryonic stage at the time the Bureau's program was discontinued. However, because of their application to many other problems, it is to be expected that their development will be continued for other uses. They would undoubtedly facilitate the evaluation of evaporation studies, and it is conceivable that use of such procedures as the energy budget and mass transfer or aerodynamic methods could be eliminated or minimized. Even though the Bureau is not presently attempting to reduce evaporation losses from its reservoirs, these losses are a major factor in project operations, and they have wide interstate and international implications in water rights and allocations.

This report is a consolidation of portions of two reports submitted to the Bureau on contract research studies of the relationship of solar reflectance of monolayer covered water surfaces to evaporation rates. Dr. J. Taylor Beard, who was a principal investigator on both contracts, prepared the consolidated version of the two reports.

Included in this publication is an informative abstract with a list of descriptors or keywords, and "Identifiers." The abstract was prepared as part of the Bureau of Reclamation's program of indexing and retrieving the literature on water resources development. The descriptors were selected from the *Thesaurus of Water Resources Terms,* which is the Bureau's standard for listing keywords.

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CHAPTER I. INTRODUCTION

The need to reduce water evaporation has caused an increasing research effort in recent years because of the great demand for water and the decrease in available supply. Several methods suggested by investigators for reducing water evaporation are: oil films spread on the water surface, a plastic cover constructed over the water surface, underground reservoirs, barriers for reducing surface winds, and monomolecular films. Use of monomolecular films, commonly known as monolayers, has received the most study in recent years. The molecules of a monolayer are long chain hydrocarbons which, upon contact with water, form an oriented layer one molecule thick. A monolayer of cetyl alcohol was reported to reduce evaporation from a pond by 39.4 percent [1].[1] Suppressing evaporation from water storages by monolayers is the most economical of all methods of conserving water now available [2].

The main purpose of this investigation was to examine critically the effect of evaporation reducing monlayers on the radiant energy transfer to water storage systems. In addition, a major search was made to find a monolayer or film-forming material with good diffusion barrier capabilities that was also capable of increasing the solar energy reflectance. A mechanism was developed which allows the prediction of the capability of a given chemical to act as a barrier to the passage of water. Experimental tests were run to determine the percentage increase in solar reflectance of the particular film or monolayer over that of a plain water surface. In addition, an analytical study was undertaken to predict the changes in evaporation which would accompany various arbitrary changes in the reflectance of the water surfaces.

Radiant energy input to the water comes from the sun and the atmosphere. Since the atmosphere receives its energy from the sun, all of the radiant energy input to the water comes from the sun. Radiant energy loss from the water is basically to outer space; however, the atmosphere may be interspersed between the water and outer space. In this investigation, the radiant energy input to a water system was considered to be made up of energy directly incident from the sun, energy from the sun which was scattered solar energy and thermal energy. It was important to differentiate between these energy quantities because the first two radiant energy quantities have the short wavelength property and the last consists of long wavelength radiant energy. Radiant energy absorption by water is dependent upon the wavelength of the incident energy. For this reason, variations in wavelength were required to obtain the radiant energy input to a water system.

Initially, it was thought that the addition of a monolayer over a water surface might significantly change the reflectance of the interface. This was expected to be important for the short wavelength energy input from the sun. For this reason, a detailed analytical and experimental program was initiated to determine the effect of common monolayer forming materials. This analysis and experimental program will be described in later sections of this report. In brief, the water surface covered with a monolayer was analyzed using Fresnel [3] equations plus thin film theory [4]. In the use of these equations the basic physical properties for water and monolayer materials in the compressed state were not available; bulk material properties were used. Experimental verification of these results was accomplished [5].

After carrying out the aforementioned investigations, it was noted that the addition of a monolayer to water resulted in significant damping of wave action. This wave action was suspected as the phenomenon which changed the visual appearance (or reflectance) of monolayer-covered water. For this reason, an analysis of the effect of water waves on the radiant energy absorption of monolayer-covered water was made [6]. This analysis indicated qualitatively the suspected fact that monolayer-covered water does have a higher reflectance due to the suppression of wave action.

In the case of water surfaces covered with a monolayer, the properties of the interface can be evaluated. Using the analytical techniques described, the radiant energy absorbed by a water storage system was evaluated. The amounts of radiant energy absorbed per day from direct solar and scattered solar irradiation depend on the geographic location, date, and relative moisture content of the atmosphere [7]. Using these parameters, a set of tables was prepared for the determination of these terms in the energy budget. Thermal energy input to a system depends on the relative moisture content and temperature of the atmosphere [7]. A tabulation of the radiant energy input to a water surface as a function of the relative humidity and temperature was prepared. These values are in Btu/hr-ft^2, rather than per day as in the previous case. The reason for this choice was to allow evaluation of this energy quantity as accurately as desired.

[1] Numbers in brackets refer to literature cited at the end of this report.

CHAPTER II. PREDICTION OF MONOLAYER EFFECTIVENESS FOR EVAPORATION REDUCTION

BACKGROUND

This part of the report is concerned with a number of properties of monomolecular films, so it is perhaps best to clarify in the beginning what these terms describe. Monolayers are, first of all, films exactly one molecule thick spread over a substrate of some type. They are of an essentially two-dimensional state where pressure is measured in terms of force per unit length, and density is characterized by an area per molecule. Likewise, this two-dimensional state can be a solid, liquid, or gas. But since a monolayer is only one molecule thick, it is invisible. The state of the monolayer can be determined from surface pressure-area (per molecule) isotherms, which are analogous to pressure-volume isotherms in three dimensions, or from measurements of surface pressure and surface viscosity where an abrupt increase or decrease in viscosity over a very short span of surface pressure indicates a phase change.

All types of monolayers can be described in the foregoing general terms. More specifically, the monolayers studied in this work were spread on a water surface and were formed from either of two classes of hydrocarbons, saturated straight-chain alcohols or acids, with chain length of six carbon atoms or more. These acids and alcohols behave the same, functionally, in the formation of the monolayer. The carboxyl (or hydroxyl) group is attracted and hydrogen-bonded by the polar water molecules (the radical is called "hydrophilic"). The carbon chain is essentially insoluble in the water ("hydrophobic") and extends completely out of the water [8]. The alinement of the molecules in the monolayer has been studied extensively by Dervichian [9] and by Langmuir [10]. They found that all of these monolayers (formed by alcohols or acids) have the same type of structure; that is, the hydrophilic radical actually becomes submerged in the water while the carbon chain extends vertically above the surface (Figure 1). This was shown by the fact that the same number of molecules of a monolayer, no matter what the chain length, always covered the same areas.

Surface tension is the primary quantity used in describing the behavior of any surface. Physically, it is the force that tends to pull the molecules of a surface together in order to minimize the surface area. Monolayers are surface active agents which interact with the surface molecules to form a new surface

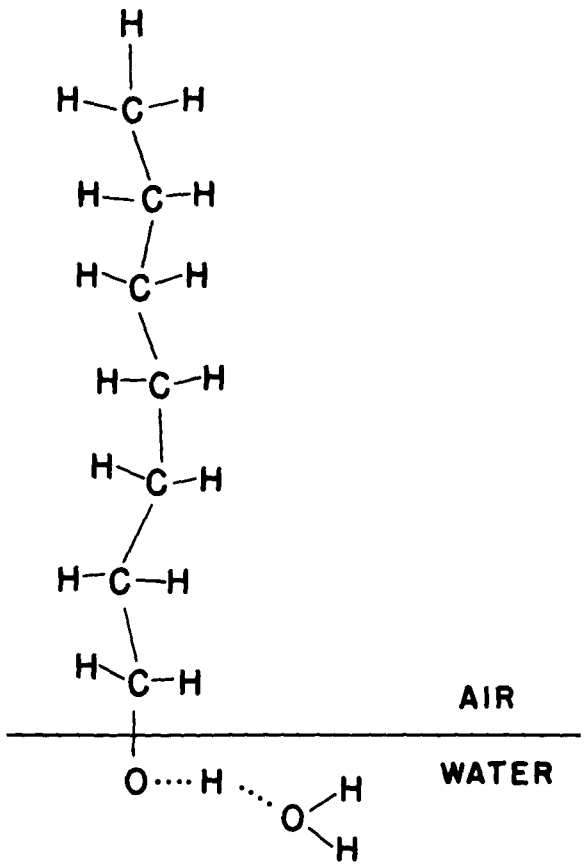

Figure 1. All monolayers have the same type of structure. The hydrophilic radical actually becomes submerged in water while the carbon chain extends vertically above the surface.

having different properties, including a lower surface tension than the original surface. This lowering of surface tension results from the insertion of molecules of the monolayer among the surface water molecules, and the long chains of these molecules repel each other, resulting in a force in the opposite direction to the surface tension. This oppositely directed (but along the surface) force is the "surface pressure." It can be defined as the difference between surface tension without a monolayer and surface tension with a monolayer [8]:

$$\pi = \gamma_W - \gamma_{Wm}. \qquad \text{(II-1)}$$

The surface pressure is, like surface tension, a function of temperature and is also proportional to the number of monolayer molecules on the surface. For this reason, the surface pressure is a convenient measure of the extent of formation of the monolayer.

The equilibrium surface pressure is the pressure at which the monolayer is completely formed (the area per molecule is a minimum). Any increase above this pressure, such as mechanically reducing the surface with movable boundaries or barriers, results in film collapse. Thus, if an excess of film molecules is available, the molecules will form a lens-shaped droplet on the monolayer surface. This phenomenon is in fact predicted from the action of a liquid of high surface free energy (surface tension) on a surface (in this case, a flexible liquid surface) of lower free energy. The appearance of this lens is a useful test for the presence and complete formation of a monolayer.

Surface viscosity is the two-dimensional analog of bulk viscosity and is an important property of a monolayer-covered surface [11]. It is a convenient property to measure in order to determine phase changes in the monolayer. Data for surface viscosity plotted with surface pressure provide an easy visualization of changes in the state of the monolayer. Figure 2 shows how a liquid to solid phase change might look on such a plot. Predictably, increasing the temperature shifts the curve down and to the right [8], [12], [13]. There are experimental difficulties in the measurement of surface viscosity quite similar to those found with bulk viscosity. The usual means, however, is a torque device such as a torsion wire suspended in a surface [13].

The discovery by Rideal [14] of the unusually high resistance to water evaporation of certain monolayers has focused attention on the mechanism of mass transport through monolayers. In fact, the resistance to evaporation has been found to be much higher for monomolecular films spread on water than for a multiple film such as an oil slick on water, which may be hundreds of times thicker than a monolayer.

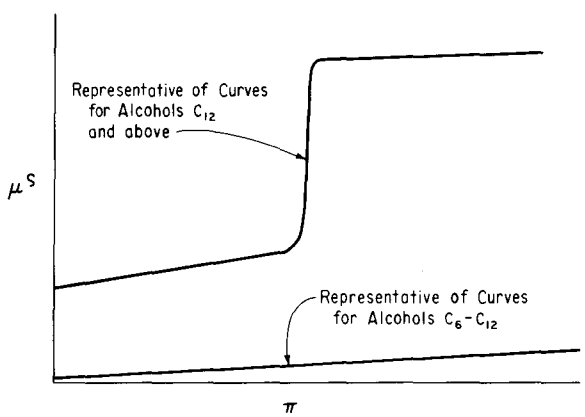

Figure 2. Liquid to solid phase change.

THEORETICAL DEVELOPMENT

In conjunction with the monolayer studies, an effort was made to determine the mechanism of evaporation suppression by monolayers. A theory was developed to predict the evaporation rate of water through a monolayer. Assuming that the monolayer acts as an energy barrier to the diffusion of vaporized water molecules at the air water interface into the air, the fraction of water molecules having enough energy E to pass the energy barrier is:

$$f = e^{-E/kT} \qquad \text{(II-2)}$$

where

k = Boltzmann's constant
T = absolute temperature.

Since this fraction is directly proportional to the permeability (p), or to the diffusivity (D_{wm}) of the monolayer, it becomes:

$$f = C_1 D_{wm} = C_1 e^{-E/kT} \qquad \text{(II-3)}$$

The difficulty is the evaluation of the energy, E. If one assumes that it is equal to the amount of work required to make a hole with the perimeter (a_o) of a water molecule in the monolayer,

$$E = \gamma_{wm} a_o$$

then,

$$D_{wm} = C_2 e^{-\gamma_{wm} a_o/kT} \qquad \text{(II-4)}$$

We know that:

$$\gamma_{wm} = \gamma_w - \pi$$

where γ_w is the surface tension of the water and is a function only of temperature. At any given temperature, γ_w is a constant and therefore:

$$\begin{aligned} D_{wm} &= C_2 e^{-(\gamma_w - \pi) a_o/kT} \\ &= C_2 e^{-\gamma_w a_o/kT \, \pi a_o/kT} \\ &= C_3 e^{\pi a_o/kT} \qquad \text{(II-5)} \end{aligned}$$

Then, if the exponential is approximated by a truncated series when $\pi a_o < kT$, we have:

$$D_{wm} = C_3[1 + \frac{\pi a_o}{kT}] \qquad \text{(II-6)}$$

For comparison, results of two other theories are presented in Table I.

EXPERIMENTAL VERIFICATION

To determine whether any of the theories were applicable, surface pressure data were taken for a number of different monolayers, all straight (unbranded) chain paraffinic alcohols and acids with chain lengths from 6 to 18. For this work, data on diffusivities of water through various normal paraffinic acid and alcohol monolayers taken by Enright [15] were used. The monolayers he studied were found to give evaporation reductions of up to 40 percent. Surface pressure measurements were made at equilibrium surface pressure conditions (complete monolayer formation) by the Wilhelmy plate method. Data for a group of the monolayers which were liquid-phase were correlated with existing diffusion (mass flux) data and the result is shown in Figure 3. The correlation shows that D_{wm} is proportional to π and not $-\pi$ as theories A and B in Table I show. The theory is actually semi-empirical since constant C_3 can be evaluated only from experiment, but it shows the same dependence of D_{wm} on π as the experimental results, and if the resulting correlation from experiment

$$D_{wm} = 0.1270\pi + 2.185 \qquad \text{(II-7)}$$

Table I.

THEORIES OF MASS TRANSFER THROUGH MONOLAYERS

A. Stokes-Einstein with surface properties

$$D_{wm} = CONST_1 \left(\frac{1}{\pi}\right)$$

B. Energy barrier theory with $E = \pi a_o$

$$D_{wm} = CONST_2 \left(1 - \frac{\pi a_o}{kT}\right)$$

C. Energy barrier with $E = \gamma_{wm} a_o$

$$D_{wm} = CONST_3 \left(1 + \frac{\pi a_o}{kT}\right)$$

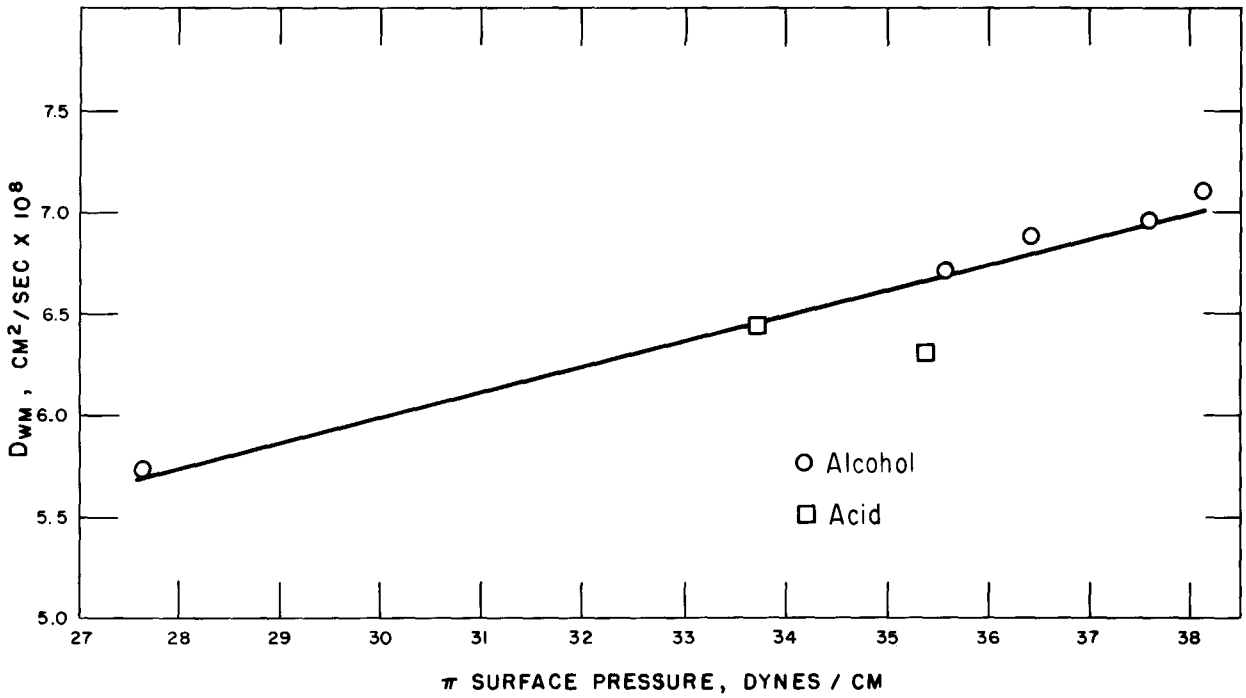

Figure 3. Data and correlation.

is altered slightly,

$$D_{wm} = 2.1875\ [1 + 0.0581\pi] \qquad \text{(II-8)}$$

the second constant agrees very closely with

$$\frac{a_o}{kT} \text{ for } T = 300^oK \text{ and } a_o$$

slightly larger than the perimeter of a water molecule (9 to 15 Å). The larger size "hole" is probably the result of hydrogen bonding at the hydrophilic end of the monolayer molecule.

The value of the correlation is that with only the measurement of surface pressure, either with a surface balance or with much simpler indicator oils, the evaporation rate from a monolayer-covered pond can be easily found. In the case of windy conditions, a simple correction factor should be applicable, but in any case the correlation will give the lower bound of the evaporation loss.

CHAPTER III. ANALYSIS OF RADIANT ENERGY INPUT TO WATER SURFACES

The analysis of the radiant energy absorbed by a water surface or a monolayer-covered water surface consisted of two basic parts. First, the characteristic reflectance of the air-water or air-monolayer-water interface had to be determined and, second, the characteristics of the incident radiant energy had to be determined. Each of these tasks will be discussed separately.

Reflectance of Interfaces

Radiant energy is generally studied in terms of electromagnetic theory. Using this model for analysis of the energy incident on a water surface, it is seen that the incident energy may be broken down into components according to the angle of incidence (the angle between the incident ray and the normal to the interface), Φ, the wave length, λ and the state of polarization. If $I_{\lambda,\Phi}$ denotes the total radiant intensity per differential wavelength at a particular angle of incidence and if dw represents the differential of the solid angle around the angle of incidence, the total radiant energy on a unit area of lake surface can be represented by:

$$q = \int_o^\infty \int_{\text{hemisphere}} I_{\lambda,\Phi} \cos \Phi \, dw \, d\lambda \qquad \text{(III-1)}$$

where $I_{\lambda,\Phi}$ is in units of power/solid angle, area projected normal to the incident ray [16].

Of the total energy, q, a portion will be reflected; and, for a deep lake, the remainder will either be absorbed at the surface or transmitted through the water until it is absorbed. The reflected energy can be represented by:

$$Rq = \int_o^\infty \int_{\text{hemisphere}} R_{\lambda,\Phi} I_{\lambda,\Phi} \cos \Phi \, dw \, d\lambda \qquad \text{(III-2)}$$

where $R_{\lambda,\Phi}$ is called the specular-monochromatic reflectance and where the quantity $R_{\lambda\Phi} I_{\lambda\Phi}$ is dependent on the polarization as well as the wavelength and angular distributions of the incoming radiant energy.

The portion of radiant energy which will be absorbed by the water and, consequently, tend to increase the water temperature and the driving potential for evaporation is represented by:

$$q(1.0 - R).$$

The study of the reflectance of water surfaces is therefore important for a theoretical understanding of the effect of radiant energy on evaporation. Lake surfaces can be classified generally as either clean or contaminated and also as either smooth or wavy.

Since the techniques of evaporation suppression most often involve contaminating the water surfaces with a monomolecular chemical film or monolayer, theoretical considerations studying the effect of these films on the reflectance of radiant energy are presented in this chapter.

Since it has been shown that monolayers have a stilling effect on water surfaces, an analytical study of the influence of water waves on the reflectance of water surfaces was also made [6].

Reflectance of Thin-Film-Covered Water Surfaces

As a first statement, it should be noted that the techniques of optics in electromagnetic theory will be used in the development of analytical expressions for reflectance. The energy ray therefore is represented by independent monochromatic sinusoidal waves in each of the two customary planes of polarization. These planes are the p-plane, which is parallel to the plane of incidence, and the s-plane, which is perpendicular to the plane of incidence. From basic electromagnetic theory, equations were developed and used in the calculation of the total energy reflectance for both the conditions of unpolarized light and arbitrarily polarized light.

In terms of the physical properties of the system, it was assumed that both the water and the film may be absorbing substances; i.e., they may be translucent or opaque. It was assumed that both substances are homogeneous and isotropic in that their optical properties were considered constant with respect to the space coordinates. The optical properties, however, were considered to be a function of wavelength. It was assumed that the reflection analysis could be made at some typical surface element and that at this location the air-film interface and the film-water interface are perfectly smooth and are parallel. It was further assumed that the thin-film-covered water surface acts as a specular reflector for all wavelengths under consideration.

Analytical expressions for reflectance are found in the Appendix. The reflectance in either plane of polarization may be considered to be a function of the following variables:

(a) The optical properties of the film and the water (index of refraction n_1, n_2, and coefficient of absorption k_1, k_2),

(b) The thickness of the film, d,

(c) The wavelength of the incident energy ray, λ, and

(d) The angle of incidence of the energy ray, Φ.

The optical properties of water are dependent on the wavelength and these values are considered to be known from the literature [17]. In Table II, values are presented for the reflectances of a clean water surface at 0.5 and 2.0 microns. The symbols used in Table II, R_s, R_p, and R refer, respectively, to the s-plane polarized, the p-plane polarized, and the unpolarized energy reflectances. The symbols Φ, n_2, and k_2 refer, respectively, to the angle of incidence, the index of refraction, and the coefficient of absorption. The latter two are a function of wavelength.

The optical properties of a particular monolayer-forming substance in its oriented and compressed monolayer state are expected to be a function of wavelength also, but few indications have been found in the literature as to what this functional relationship might be. From the absorption data of bulk cetyl and stearyl alcohol in the literature, rough calculations indicate that the coefficient of absorption is small, with a maximum value of approximately 0.007 at 3.4 microns [18]. The thickness of the monolayer was assumed to be 24 Å, which is the average of values calculated by Hofmeister [19] for the thickness of palmetic and stearic acid monolayers.

Thus, the reflectance of an energy ray having a particular wavelength and a particular angle of incidence onto a monolayer-covered surface has only two independent and unknown variables, n_1 and k_1. Various values of n_1, k_1, and film thickness were assumed, and a computer program was written to aid in the analysis. The results for unpolarized energy at 0.5 and 2.0 microns and at various angles of incidence are presented in Tables III and IV. Figure 4 shows the variation of unpolarized reflectance of a monolayer as a function of the angle of incidence.

As it was desirable to know the change in the reflectance of water due to the application of a monolayer or a film, a second computer program was written. This program provided the calculation of the ratio of the monochromatic reflectance at various angles of incidence for a water surface having a monolayer or film to the similar reflectance of a clean water surface. Tables V and VI present the results for unpolarized incident energy. Figures 5 through 8 show graphically the variation of the unpolarized reflectance ratio with the various properties of the film at 0.5 micron.

From the tables and graphs, it is seen that the reflectance of a monolayer-covered surface increases with an increase in the optical properties, n_1 and k_1, of the monolayer. It is also seen that under certain conditions, the reflectances will be less than those of a clean water surface. Further, it is noted that by greatly increasing the thickness of the surface film, it is possible to significantly increase the reflectance. However, this does not always hold true, as in the case of small values of n_1 and k_1.

Table II

REFLECTANCE OF CLEAN WATER SURFACES

Φ	R_s	R_p	R	n_2	k_2
			0.5 micron		
0	0.0207	0.0207	0.0207	1.336	0.00000
20	.0249	.0169	.0209	1.336	.00000
40	.0437	.0060	.0249	1.336	.00000
60	.1162	.0043	.0603	1.336	.00000
80	.4588	.2390	.3489	1.336	.00000
			2.0 microns		
0	0.0174	0.0174	0.0174	1.304	0.00110
20	.0210	.0141	.0176	1.304	.00110
40	.0376	.0048	.0212	1.304	.00110
60	.1037	.0047	.0542	1.304	.00110
80	.4386	.2367	.3377	1.304	.00110

Reflectance of Water Wave Surfaces

The following analysis is an attempt to determine the influence of water waves on reflectance. We shall assume that the water waves are perfectly smooth two-dimensional sine waves and that their wavelengths are large in comparison with the wavelength of the incident energy. The equations presented by Simon [20] for the reflectance of a ray of energy by a single absorbing surface are known, and the optical properties of water are selected to correspond to the energy wavelength of 1.0μ.

The hemispherical reflectance of a flat surface, as indicated by Wiebelt [16], is defined as

$$R = \frac{\int_{2\pi} R(\Phi,\theta)\, I(\Phi,\theta) \cos\Phi \, dw}{\int_{2\pi} I(\Phi,\theta) \cos\Phi \, dw} \qquad \text{(III-3)}$$

where $R(\Phi,\theta)$ is the reflectance of each incident energy ray passing through the solid angle dw which is oriented with angles Φ and θ. The intensity of the incident ray is $I(\Phi,\theta)$. The geometry for this integration is shown in Figure 9.

For the special case of diffuse incident energy, the above equation reduces to

$$R_d = \frac{1}{\pi} \int_{2\pi} R(\Phi,\theta) \cos\Phi \, dw$$

which can be shown to be

$$R_d = \frac{1}{\pi} \int_0^{2\pi} \int_0^{\pi/2} R(\Phi,\theta) \cos\Phi \sin\Phi \, d\Phi \, d\theta .$$

If the surface is not normal to the y axis, the actual angle of incidence of the energy ray depends on the slope a. For sine wave contours, this is illustrated in Figures 10 and 11, where the energy ray is oriented with $\theta = 0^o$. A procedure for calculating the slope of each wave element as a function of the projection of the angle of incidence into the x-y plane is presented in Reference 39. It can be shown that for arbitrary values of θ, the actual angle of incidence for a wave element having a slope a is

$$\text{arc cos}\,[\cos a \cos\Phi - \sin a \sin\Phi \cos\theta] .$$

If we neglect secondary reflections, the average reflectance for an energy ray with orientation Φ and θ is

$$R(\Phi,\theta) = \frac{1}{\lambda} \int_0^{\lambda} R(\Phi,\theta,x)\, dx.$$

Table III

PERCENT REFLECTANCE OF FILM-COVERED WATER SURFACES
HAVING UNPOLARIZED INCIDENT ENERGY
AT 0.5 MICRON

Thickness of film		1 molecule			10 molecules			100 molecules		
k_1	Φ \ n_1	1.3	1.4	1.5	1.3	1.4	1.5	1.3	1.4	1.5
	0	2.07	2.07	2.08	1.97	2.32	2.93	1.75	3.21	6.28
	20	2.09	2.09	2.10	1.99	2.33	2.91	1.86	3.06	6.05
0.0000	40	2.48	2.49	2.49	2.40	2.71	3.26	2.44	2.99	5.52
	60	6.02	6.03	6.04	5.92	6.30	6.94	5.95	6.09	7.76
	80	34.89	34.89	34.90	34.74	35.24	35.99	34.11	35.00	35.49
	0	2.07	2.07	2.08	1.97	2.32	2.94	1.75	3.21	6.28
	20	2.09	2.09	2.10	1.99	2.33	2.92	1.86	3.06	6.05
0.0001	40	2.48	2.49	2.49	2.40	2.71	3.26	2.44	2.99	5.52
	60	6.02	6.03	6.04	5.92	6.29	6.94	5.95	6.08	7.72
	80	34.89	34.89	34.90	34.74	35.24	35.98	34.10	35.00	35.48
	0	2.08	2.08	2.09	2.07	2.43	3.05	1.88	3.29	6.13
	20	2.10	2.10	2.11	2.09	2.43	3.03	1.97	3.16	5.93
0.0100	40	2.49	2.50	2.51	2.50	2.82	3.38	2.48	3.14	5.53
	60	6.04	6.04	6.05	6.06	6.44	7.09	5.78	6.25	7.99
	80	34.91	34.92	34.93	34.96	35.45	36.17	33.64	35.10	35.96
	0	2.18	2.20	2.22	3.01	3.48	4.18	2.71	3.97	5.71
	20	2.19	2.21	2.24	3.00	3.46	4.14	2.65	3.90	5.67
0.1000	40	2.59	2.61	2.64	3.40	3.85	4.50	2.71	4.00	5.82
	60	6.17	6.19	6.22	7.31	7.78	8.47	5.60	7.40	9.42
	80	35.12	35.13	35.14	36.90	37.25	37.77	33.99	36.68	38.65
	0	3.24	3.44	3.65	16.76	18.81	20.95	25.50	27.47	29.42
	20	3.25	3.45	3.67	16.67	18.72	20.87	25.56	27.52	29.46
1.000	40	3.69	3.89	4.12	17.06	19.07	21.17	26.60	28.38	30.17
	60	7.46	7.67	7.90	21.39	22.98	24.65	32.41	33.39	34.46
	80	36.30	36.39	36.50	47.71	47.68	47.68	58.76	58.07	57.47

Table IV

PERCENT REFLECTANCE OF FILM-COVERED WATER SURFACES
HAVING UNPOLARIZED INCIDENT ENERGY
AT 2.0 MICRONS

Thickness of film		1 molecule			10 molecules			100 molecules		
k_1	n_1 / Φ	1.3	1.4	1.5	1.3	1.4	1.5	1.3	1.4	1.5
	0	1.74	1.74	1.74	1.74	1.76	1.81	1.67	3.47	6.13
	20	1.76	1.76	1.76	1.75	1.78	1.82	1.69	3.43	6.05
0.0000	40	2.12	2.12	2.12	2.11	2.14	2.18	2.05	3.76	6.34
	60	5.42	5.42	5.42	5.41	5.44	5.49	5.32	7.51	10.53
	80	33.76	33.76	33.77	33.76	33.80	33.86	33.61	36.68	39.99
	0	1.74	1.74	1.74	1.74	1.76	1.81	1.67	3.47	6.14
	20	1.76	1.76	1.76	1.75	1.78	1.82	1.69	3.43	6.05
0.0001	40	2.12	2.12	2.12	2.11	2.14	2.18	2.05	3.76	6.34
	60	5.42	5.42	5.42	5.41	5.44	5.49	5.33	7.51	10.53
	80	33.76	33.76	33.76	33.76	33.80	33.86	33.61	36.68	39.99
	0	1.74	1.74	1.74	1.76	1.79	1.84	1.80	3.57	6.17
	20	1.76	1.76	1.76	1.78	1.81	1.85	1.82	3.53	6.09
0.0100	40	2.12	2.12	2.12	2.14	2.17	2.21	2.20	3.87	6.40
	60	5.42	5.42	5.42	5.45	5.48	5.53	5.58	7.70	10.61
	80	33.77	33.77	33.77	33.82	33.86	33.92	34.09	36.96	40.08
	0	1.77	1.77	1.77	1.99	2.06	2.15	3.30	4.91	7.15
	20	1.78	1.79	1.79	2.00	2.07	2.15	3.31	4.88	7.08
0.1000	40	2.14	2.15	2.15	2.36	2.43	2.52	3.79	5.32	7.46
	60	5.45	5.46	5.46	5.78	5.85	5.94	7.99	9.68	11.92
	80	33.83	33.83	33.83	34.38	34.41	34.48	38.11	39.70	41.48
	0	2.00	2.04	2.09	4.90	5.44	6.03	28.49	30.63	32.69
	20	2.02	2.06	2.11	4.90	5.45	6.04	28.23	30.41	32.50
1.000	40	2.39	2.43	2.48	5.36	5.91	6.52	28.38	30.50	32.54
	60	5.76	5.81	5.87	9.25	9.79	10.32	32.82	34.27	35.70
	80	34.16	34.20	34.24	37.57	37.75	37.95	57.86	57.53	57.24

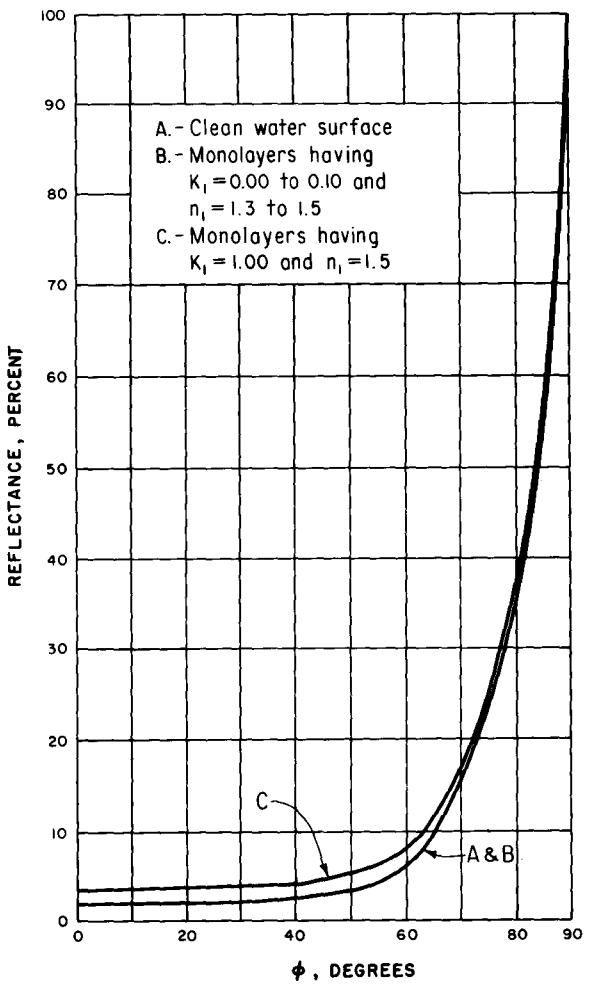

Figure 4. Unpolarized energy reflectance for a monolayer-covered water surface at 0.5 micron.

To aid in the evaluation of the above integral, a computer program making use of the Weddle integration rule was written. The results for various ratios of amplitude to wavelength and for four values of θ are presented in Figures 12, 13, 14, and 15.

An additional computer program aided in the evaluation of the following triple integration for the effective diffuse reflectance of a water wave surface

$$R_d = \frac{1}{\pi}\int_0^{2\pi}\int_0^{\pi/2}\left[\frac{1}{\lambda}\int_0^{\lambda} R(\Phi, \theta, x)dx\right] \cdot \cos\Phi \sin\Phi \, d\Phi \, d\theta.$$

These results are presented in Figure 16.

From an analysis of the information given in Figures 12, 13, 14, and 15, it is obvious that water waves do affect the magnitude of the reflected radiant energy. For near-normal incident energy, the presence of water waves tends to increase the reflectance of water surfaces. As mentioned previously, the secondary reflections were not considered in the analytical model, and, consequently, the increase in reflectance noted under the near-normal incidence conditions is exaggerated. Under the conditions of large angles of incidence, secondary reflections are improbable, and water waves are seen to decrease the reflectance of water substantially. The influence of secondary reflections should be slight for water waves with A/λ (amplitude to wavelength) values below 0.10. For waves with A/λ values above this, the importance of secondary reflections increases.

The results in Figure 16 are representative of the total reflectance which would be noticed under very overcast skies. They indicate that water waves may reduce the reflected energy by more than 20 percent. Because of secondary reflectance, it is expected that the actual diffuse reflectance should decrease more rapidly with A/λ than is indicated in Figure 16.

The analytical model was developed under the assumption that the contour of the water wave was that of a two-dimensional sine wave and that the incident ray was 1.0μ energy. Although it is certain that water waves are not sine waves and that the actual energy covers a wide spectrum, we believe that the variable of the amplitude to wavelength is important and that the trends indicated in Figures 12, 13, 14, and 15 are valid.

For nondiffuse incident energy, the values for $R(\Phi,\theta)$ presented in Figures 12, 13, 14, and 15 can be used to approximate the reflectance of each energy ray.

Further, it should be noted that evaporation-reducing monolayers reduce the magnitude of water waves. Consequently, by knowing the ratio of the amplitude to the wavelength of the water waves before and after the monolayer is applied, and by knowing the angular distribution of the incident energy, we can predict the amount of change in the reflectance due to the water wave damping of the monolayer.

Incident Radiant Energy

Direct Solar Energy.—The solar energy directly incident on the water surface was determined using the standard solar-radiation curves presented by Parry Moon [7]. These curves for the solar energy incident on the outer fringes of the earth's atmosphere were

Table V

RATIO OF REFLECTANCE OF FILM-COVERED WATER SURFACES TO REFLECTANCE OF WATER SURFACES WITHOUT A FILM AT 0.5 MICRON

Thickness of film		1 molecule			10 molecules			100 molecules		
k_1	n_1 / Φ	1.3	1.4	1.5	1.3	1.4	1.5	1.3	1.4	1.5
	0	1.000	1.000	1.005	0.952	1.120	1.415	0.845	1.551	3.034
	20	1.000	1.000	1.005	0.952	1.115	1.392	0.890	1.464	2.895
0.0000	40	0.996	1.000	1.000	0.964	1.088	1.309	0.980	1.201	2.217
	60	0.998	1.000	1.002	0.982	1.045	1.151	0.987	1.010	1.287
	80	1.000	1.000	1.000	0.996	1.010	1.032	0.978	1.003	1.017
	0	1.000	1.000	1.005	0.952	1.121	1.420	0.845	1.551	3.034
	20	1.000	1.000	1.005	0.952	1.115	1.397	0.890	1.464	2.895
0.0001	40	0.996	1.000	1.000	0.964	1.088	1.309	0.980	1.201	2.217
	60	0.998	1.000	1.002	0.982	1.043	1.151	0.987	1.008	1.287
	80	1.000	1.000	1.000	0.996	1.010	1.031	0.977	1.003	1.017
	0	1.005	1.005	1.010	1.000	1.174	1.473	0.908	1.589	2.961
	20	1.005	1.005	1.010	1.000	1.163	1.450	0.943	1.512	2.837
0.0100	40	1.000	1.004	1.008	1.004	1.132	1.357	0.996	1.261	2.221
	60	1.002	1.002	1.003	1.005	1.068	1.176	0.959	1.037	1.325
	80	1.001	1.001	1.001	1.002	1.016	1.037	0.964	1.006	1.031
	0	1.053	1.063	1.072	1.454	1.681	2.019	1.301	1.918	2.758
	20	1.048	1.057	1.072	1.435	1.655	1.981	1.268	1.866	2.713
0.1000	40	1.040	1.048	1.060	1.365	1.546	1.807	1.088	1.606	2.337
	60	1.023	1.027	1.032	1.212	1.290	1.405	0.929	1.227	1.562
	80	1.007	1.007	1.007	1.058	1.068	1.083	0.974	1.051	1.108
	0	1.565	1.662	1.763	8.097	9.087	10.12	12.31	13.27	14.21
	20	1.555	1.651	1.756	7.976	8.957	9.986	12.23	13.17	14.10
1.0000	40	1.482	1.562	1.655	6.851	7.659	8.502	10.68	11.40	12.12
	60	1.237	1.272	1.310	3.547	3.811	4.088	5.375	5.537	5.715
	80	1.040	1.043	1.046	1.367	1.367	1.367	1.684	1.664	1.647

Table VI

RATIO OF REFLECTANCE OF FILM-COVERED WATER SURFACES TO REFLECTANCE OF WATER SURFACES WITHOUT A FILM AT 2.0 MICRONS

Thickness of film		1 molecule			10 molecules			100 molecules		
k_1	n_1 / Φ	1.3	1.4	1.5	1.3	1.4	1.5	1.3	1.4	1.5
	0	1.000	1.000	1.000	1.000	1.011	1.040	0.960	1.994	3.523
	20	1.000	1.000	1.000	0.994	1.011	1.034	0.960	1.949	3.438
0.0000	40	1.000	1.000	1.000	0.995	1.009	1.029	0.967	1.774	2.991
	60	1.000	1.000	1.000	0.998	1.004	1.013	0.982	1.386	1.943
	80	1.000	1.000	1.000	1.000	1.001	1.003	0.995	1.086	1.184
	0	1.000	1.000	1.000	1.000	1.011	1.040	0.960	1.994	3.529
	20	1.000	1.000	1.000	0.994	1.011	1.034	0.960	1.949	3.438
0.0001	40	1.000	1.000	1.000	0.995	1.009	1.028	0.967	1.774	2.991
	60	1.000	1.000	1.000	0.998	1.004	1.013	0.983	1.386	1.943
	80	1.000	1.000	1.000	1.000	1.001	1.003	0.995	1.086	1.184
	0	1.000	1.000	1.000	1.011	1.029	1.057	1.034	2.051	3.546
	20	1.000	1.000	1.000	1.011	1.028	1.051	1.034	2.006	3.460
0.0100	40	1.000	1.000	1.000	1.009	1.024	1.042	1.038	1.825	3.019
	60	1.000	1.000	1.000	1.005	1.011	1.020	1.030	1.421	1.958
	80	1.000	1.000	1.000	1.001	1.003	1.004	1.009	1.094	1.187
	0	1.017	1.017	1.017	1.144	1.184	1.236	1.897	2.822	4.109
	20	1.011	1.017	1.017	1.136	1.176	1.222	1.881	2.773	4.023
0.1000	40	1.009	1.014	1.014	1.113	1.146	1.189	1.788	2.509	3.519
	60	1.006	1.007	1.007	1.066	1.079	1.096	1.474	1.786	2.199
	80	1.002	1.002	1.002	1.018	1.019	1.021	1.129	1.176	1.228
	0	1.149	1.172	1.201	2.816	3.126	3.466	16.37	17.60	18.79
	20	1.148	1.170	1.199	2.784	3.097	3.432	16.04	17.28	18.47
1.0000	40	1.127	1.146	1.170	2.528	2.788	3.075	13.39	14.39	15.35
	60	1.063	1.072	1.083	1.707	1.806	1.917	6.055	6.323	6.587
	80	1.012	1.013	1.014	1.113	1.118	1.124	1.713	1.703	1.695

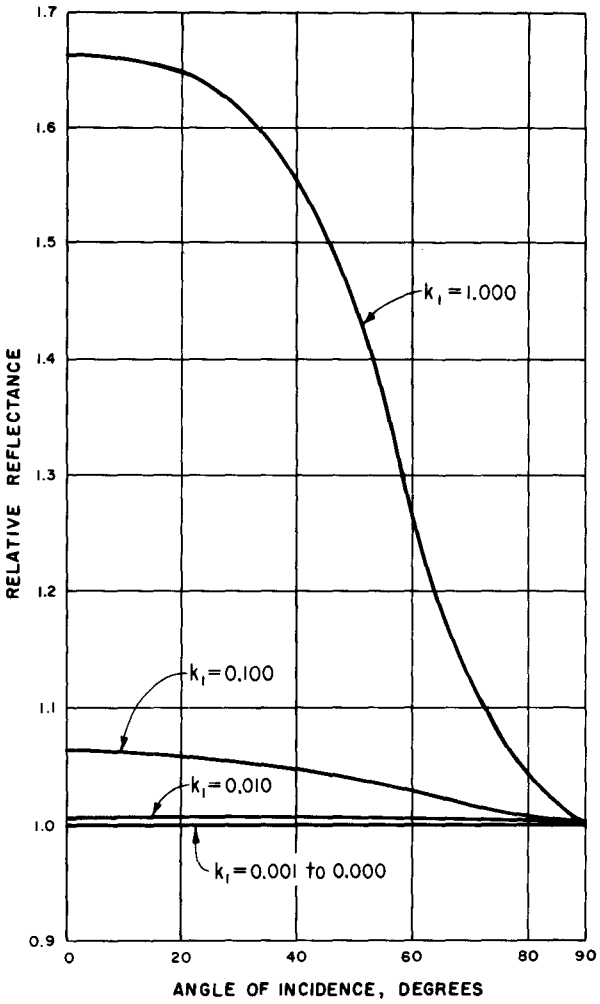

Figure 5. Relative reflectance of unpolarized energy reflected from a monolayer-covered water surface with n_1 = 1.4 and k_1 variable at 0.5 micron.

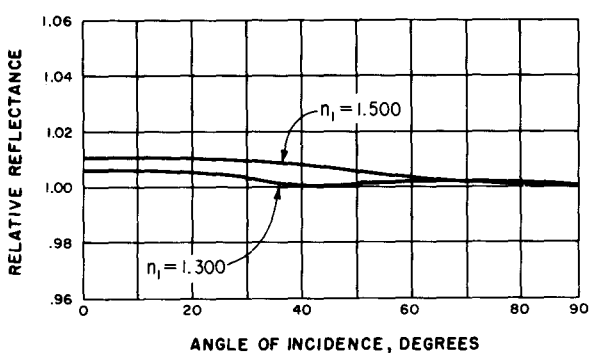

Figure 6. Relative reflectance of unpolarized energy reflected from a monolayer-covered water surface with k_1 = 0.01 and n_1 variable at 0.5 micron.

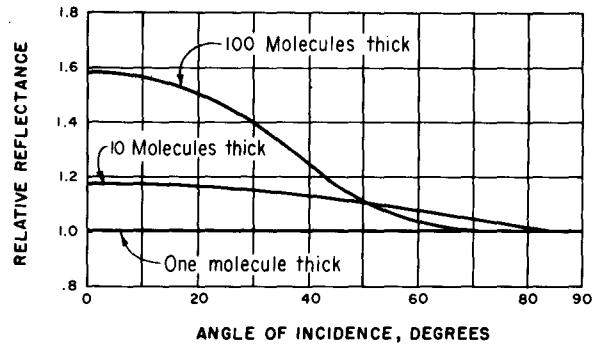

Figure 7. Relative reflectance of unpolarized energy reflected from a film-covered water surface with k_1 = 0.00, n_1 = 1.4, and with variable film thickness at 0.5 micron.

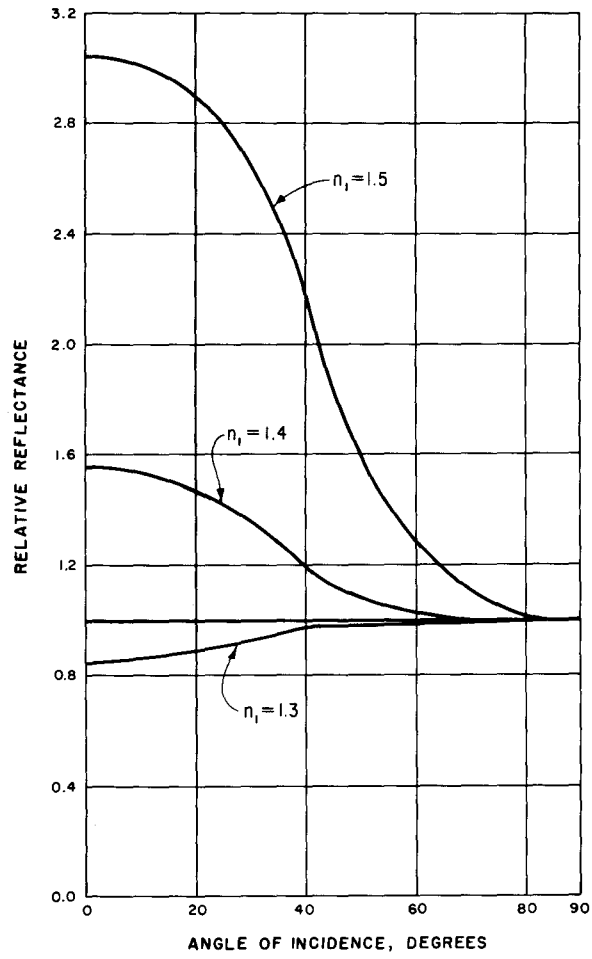

Figure 8. Relative reflectance of unpolarized energy reflected from a 100 molecule-thick-film-covered water surface with k_1 = 0.00 and n_1 variable at 0.5 micron.

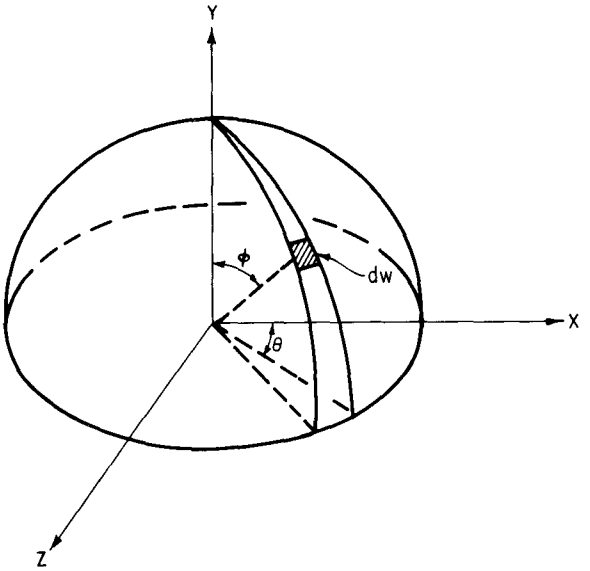

Figure 9. Geometry for integration.

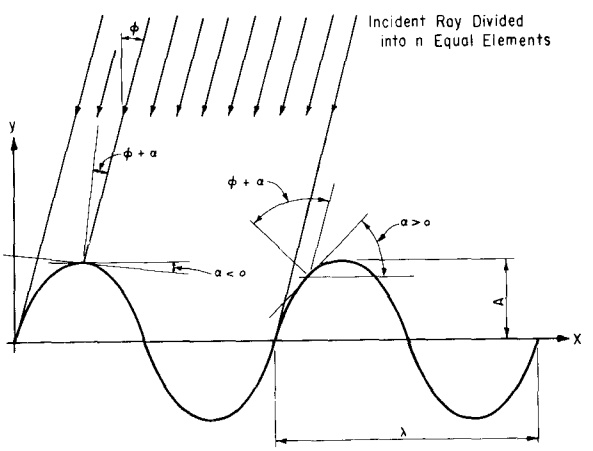

Figure 10. Energy incident on water wave with no shadow.

modified to account for atmospheric attenuation. Attenuation of the atmosphere depends on the slant path distance, barometric pressure, moisture in the air, dust in the air, and ozone content of the upper levels. In this study, variations of all variables except ozone content were considered. The results of the analysis are given in Table VII in terms of zenith distance or air mass. Zenith distance is the angle between an observer's local zenith (normal to the earth's surface) and a line drawn to the sun's position. Air mass is defined as 1/cos Φ where Φ is the zenith distance. Values are presented in the tables for the normal irradiation and the energy absorption. Normal irradiation is the amount of power per unit area on a surface oriented normal to the sun's rays. Energy absorption is the amount of power per unit area which would be absorbed by a quiescent horizontal water surface.

Scattered Solar Energy.—Solar energy scattered by the atmosphere and then incident on a water surface was determined as a function of the zenith distance from sky maps presented by Bennett, et al. [21]. This was accomplished by cross-plotting the sky maps. Values of the sky radiance in watts/square meter-steradian were plotted for constant zenith angles as a function of azimuth angle. The curves were planimetered to obtain an average value for each zenith angle. The results of these calculations are given in Table VIII for the three locations included in the report by Bennett, et al. [21].

Thermal Energy.—Thermal energy incident on water surface was obtained using the technique described by Bennett, et al. [21]. This energy is emitted by the warm atmosphere around the earth and is primarily dependent on the atmospheric temperature T and the water vapor present. The technique required the evaluation of the following quantity:

$$\sigma T^4 \int_0^{\pi/2} [1-\exp(0.776 \ln[0.52 + 0.065\, e^{1/2}] \cdot \cos^{1/2}\theta \times \sin 2\theta \, d\theta$$

where

- σ is the Stefan Boltzmann constant
- θ is the angle from the horizon to a line into the sky (90-zenith angle)
- e is the absolute pressure of the water vapor in the atmosphere in mm of Hg.

Since this averaged the incident energy over all zenith angles, it was not necessary to consider angular variations in reflectance for the water surface. An average water reflectance for long wavelength diffuse irradiation of 0.866 was used. This was obtained from the work of Brunt [22]. Results of this are presented in the chapter on energy budget considerations.

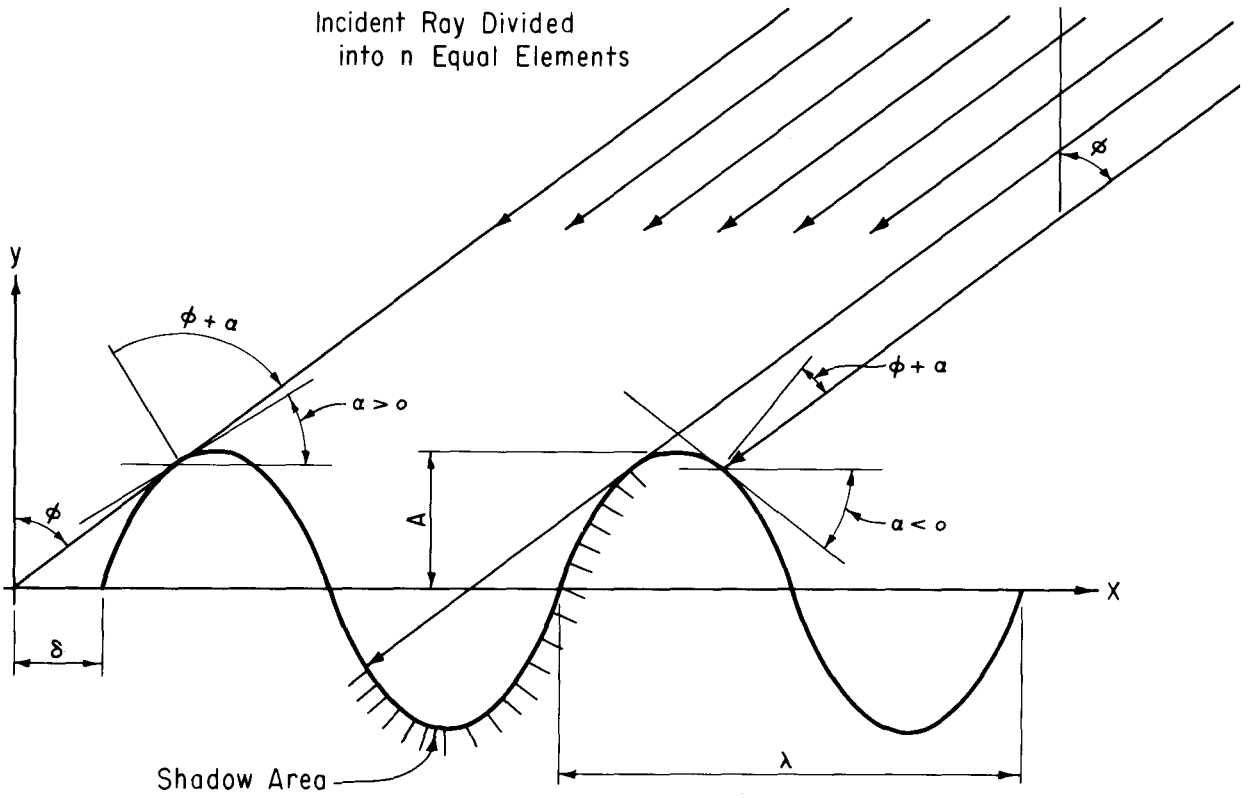

Figure 11. Energy incident on water wave with a shadow.

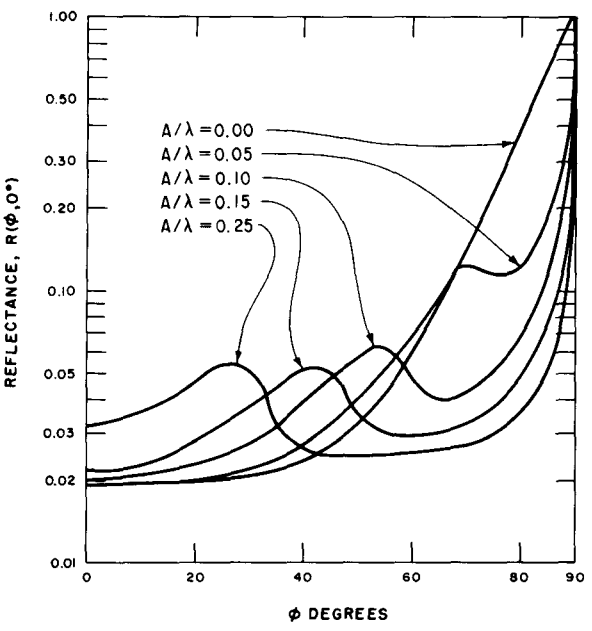

Figure 12. Reflectance from a water wave with $\theta = 0$.

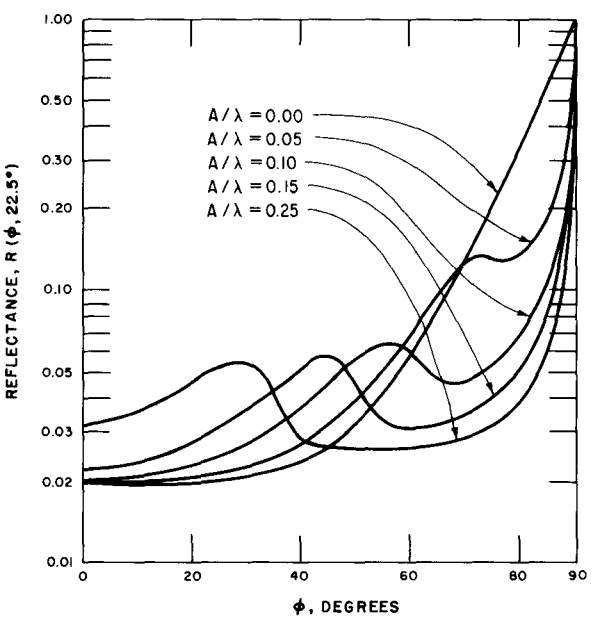

Figure 13. Reflectance from a water wave with $\theta = 22.5^{o}$.

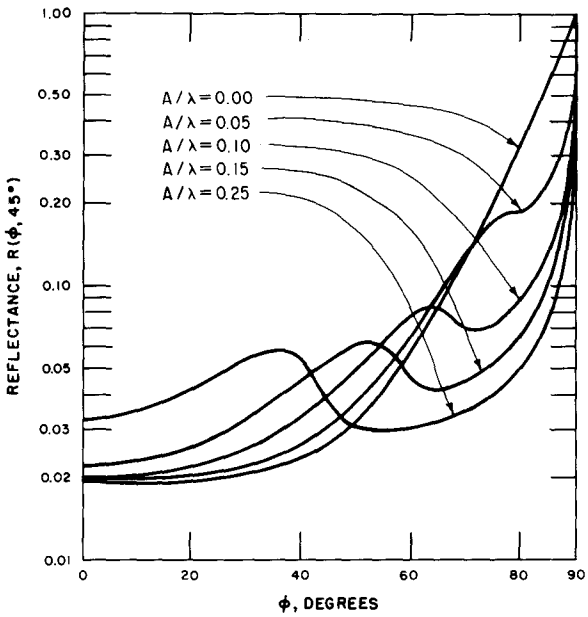

Figure 14. Reflectance from a water wave with $\theta = 45^{o}$.

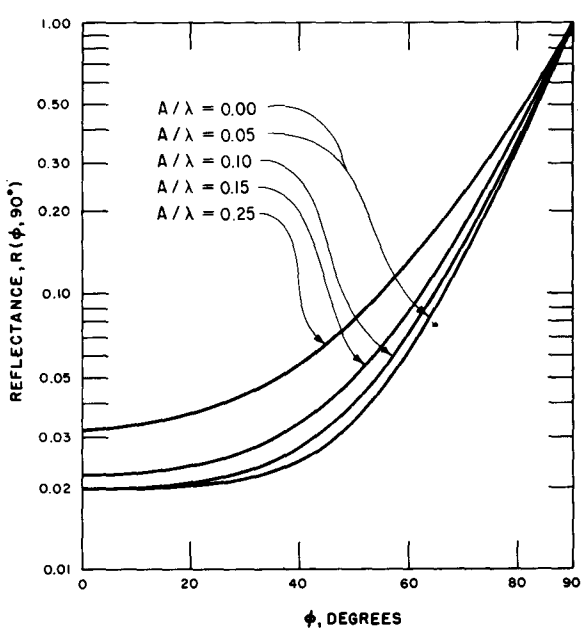

Figure 15. Reflectance from a water wave with $\theta = 90^{o}$.

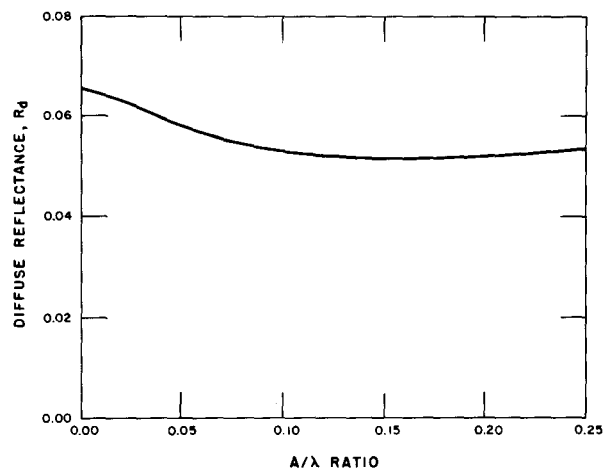

Figure 16. Diffuse reflectance of a water wave surface.

CHAPTER IV
ENERGY BUDGET CONSIDERATIONS

As a result of the analytical and experimental work done, it was possible to prepare detailed values of radiant energy gain by a water system. These values were prepared for a smooth water surface, since the monolayer-covered water is likely to be smooth when compared to ordinary water surfaces.

In order to prepare tabular values for use, it was necessary to choose latitude values. Since the most likely location for application of evaporation reduction techniques is in the southern portions of the United States, latitudes corresponding to these regions were chosen.

The techniques used in obtaining tabulated values are described in the following discussion.

Determination of the Solar Input

Zenith Angle Determination.—The solar zenith angle at any position on the earth and at any time may be determined from the Nautical Almanac [23]. Sunrise and sunset times are also given by the Almanac. Using the Almanac for 1966, the values of the solar zenith angle for the dates February 4, March 21, May 6, June

Table VII

DIRECT SOLAR ENERGY ABSORPTION TABLES

Zenith distance	Air mass	Pressure 760 mm of Hg Water vapor 10 mm precipitable Ozone 2.8 mm Dust 300 particle/cc	
		Normal irradiation in watt/sq meter	Energy absorption in watt/sq meter
0	1.0000	973.354	953.869
5	1.0038	972.536	949.439
10	1.0154	970.056	936.105
15	1.0353	965.845	914.210
20	1.0642	959.779	883.683
25	1.1034	951.670	844.840
30	1.1547	941.255	797.982
35	1.2208	928.176	743.473
40	1.3054	911.914	681.740
45	1.4142	891.794	613.288
50	1.5557	866.837	538.721
55	1.7434	835.628	458.801
60	2.0000	796.010	374.590
65	2.3662	744.937	287.697
70	2.9238	679.675	200.831
75	3.8637	581.438	118.765
80	5.7588	439.787	49.945

Table VII—Continued

Zenith distance	Air mass	Pressure 760 mm of Hg Water vapor 20 mm precipitable Ozone 2.8 mm Dust 300 particle/cc	
		Normal irradiation in watt/sq meter	Energy absorption in watt/sq meters
0	1.0000	911.080	892.778
5	1.0038	910.212	888.532
10	1.0154	907.580	875.828
15	1.0353	903.113	854.770
20	1.0642	896.682	825.530
25	1.1034	888.093	788.343
30	1.1547	877.069	743.511
35	1.2208	863.227	691.400
40	1.3054	846.035	632.440
45	1.4142	842.756	567.138
50	1.5557	798.349	496.109
55	1.7434	765.314	420.144
60	2.0000	723.437	340.353
65	2.3662	669.349	258.459
70	2.9238	597.713	177.353
75	3.8637	499.753	102.045
80	5.7588	360.795	40.954

Table VII—Continued

Zenith distance	Air mass	Pressure 760 mm of Hg Water vapor 30 mm precipitable Ozone 2.8 mm Dust 300 particle/cc	
		Normal irradiation in watt/sq meter	Energy absorption in watt/sq meter
0	1.0000	911.080	892.778
5	1.0038	910.212	888.532
10	1.0154	907.580	875.828
15	1.0353	903.113	854.770
20	1.0642	896.682	825.530
25	1.1034	888.093	788.343
30	1.1547	877.069	743.511
35	1.2208	863.227	691.400
40	1.3054	846.035	632.440
45	1.4142	824.756	567.138
50	1.5557	798.349	496.109
55	1.7434	765.314	420.144
60	2.0000	723.437	340.353
65	2.3662	669.349	258.459
70	2.9238	597.713	177.353
75	3.8637	499.753	102.045
80	5.7588	360.795	40.954

Table VII—Continued

Zenith distance	Air mass	Pressure 760 mm of Hg Water vapor 40 mm precipitable Ozone 2.8 mm Dust 300 particle/cc	
		Normal irradiation in watt/sq meter	Energy absorption in watt/sq meter
0	1.0000	891.280	873.360
5	1.0038	890.387	869.163
10	1.0154	887.681	856.609
15	1.0353	883.087	835.801
20	1.0642	876.472	806.908
25	1.1034	867.635	770.168
30	1.1547	856.292	725.884
35	1.2208	842.049	674.424
40	1.3054	824.367	616.228
45	1.4142	802.499	551.819
50	1.5557	775.407	481.839
55	1.7434	741.615	407.120
60	2.0000	698.980	328.831
65	2.3662	644.290	248.768
70	2.9238	572.567	169.877
75	3.8637	475.804	97.143
80	5.7588	341.039	38.705

Table VII—Continued

Zenith distance	Air mass	Pressure 620 mm of Hg Water vapor 10 mm precipitable Ozone 2.8 mm Dust 300 particle/cc	
		Normal irradiation in watt/sq meter	Energy absorption in watt/sq meter
0	1.0000	988.874	969.062
5	1.0038	988.090	964.609
10	1.0154	985.716	951.283
15	1.0353	981.683	929.186
20	1.0642	975.871	898.484
25	1.1034	968.096	859.407
30	1.1547	958.100	812.248
35	1.2208	945.525	757.360
40	1.3054	929.879	695.156
45	1.4142	910.475	626.120
50	1.5557	886.345	550.830
55	1.7434	856.083	470.012
60	2.0000	817.573	384.676
65	2.3662	767.468	296.381
70	2.9238	700.126	207.774
75	3.8637	605.220	123.608
80	5.7588	462.026	52.462

Table VII—Continued

Zenith distance	Air mass	Pressure 620 mm of Hg Water vapor 20 mm precipitable Ozone 2.8 mm Dust 300 particle/cc	
		Normal irradiation in watt/sq meter	Energy absorption in watt/sq meter
0	1.0000	951.491	932.386
5	1.0038	950.678	928.044
10	1.0154	948.216	915.051
15	1.0353	944.036	893.511
20	1.0642	938.017	863.592
25	1.1034	929.978	825.531
30	1.1547	919.659	779.622
35	1.2208	906.698	726.224
40	1.3054	890.595	665.754
45	1.4142	870.646	598.698
50	1.5557	845.849	525.631
55	1.7434	814.737	447.281
60	2.0000	775.086	364.655
65	2.3662	723.389	279.329
70	2.9238	653.845	194.012
75	3.8637	556.338	113.603
80	5.7588	412.438	46.818

Table VII—Continued

Zenith distance	Air mass	Pressure 620 mm of Hg Water vapor 30 mm precipitable Ozone 2.8 mm Dust 300 particle/cc	
		Normal irradiation in watts/sq meter	Energy absorption in watts/sq meter
0	1.0000	926.509	907.882
5	1.0038	925.675	903.612
10	1.0154	923.147	890.836
15	1.0353	918.856	869.656
20	1.0642	912.674	840.238
25	1.1034	904.412	802.815
30	1.1547	893.799	757.680
35	1.2208	880.451	705.187
40	1.3054	863.861	645.751
45	1.4142	843.280	579.861
50	1.5557	817.675	508.104
55	1.7434	785.542	431.234
60	2.0000	744.646	350.315
65	2.3662	691.544	267.013
70	2.9238	620.719	184.164
75	3.8637	522.914	106.762
80	5.7588	382.134	43.367

Table VII—Continued

Zenith distance	Air mass	Pressure 620 mm of Hg Water vapor 40 mm precipitable Ozone 2.8 mm Dust 300 particle/cc	
		Normal irradiation in watt/sq meter	Energy absorption in watt/sq meter
0	1.0000	906.672	888.247
5	1.0038	905.812	884.207
10	1.0154	903.210	871.581
15	1.0353	898.790	850.649
20	1.0642	892.423	821.579
25	1.1034	883.911	784.602
30	1.1547	872.976	740.014
35	1.2208	859.229	688.171
40	1.3054	842.138	629.498
45	1.4142	820.961	564.500
50	1.5557	794.662	493.790
55	1.7434	761.762	418.165
60	2.0000	720.090	338.747
65	2.3662	666.364	257.275
70	2.9238	595.420	176.693
75	3.8637	498.768	101.819
80	5.7588	362.111	41.089

Table VII—Continued

Zenith distance	Air mass	Pressure 785 mm of Hg Water vapor 10 mm precipitable Ozone 2.8 mm Dust 300 particle/cc	
		Normal irradiation in watt/sq meter	Energy absorption in watt/sq meter
0	1.0000	970.662	951.234
5	1.0038	969.838	946.808
10	1.0154	967.341	933.567
15	1.0353	963.100	911.614
20	1.0642	956.991	881.119
25	1.1034	948.820	842.319
30	1.1547	938.343	795.516
35	1.2208	925.174	741.075
40	1.3054	908.817	679.428
45	1.4142	888.580	611.081
50	1.5557	863.489	536.643
55	1.7434	832.140	456.885
60	2.0000	792.441	372.871
65	2.3662	741.117	286.225
70	2.9238	672.724	199.661
75	3.8637	577.464	117.956
80	5.7588	436.113	49.529

Table VII—Continued

Zenith distance	Air mass	Pressure 785 mm of Hg Water vapor 20 mm precipitable Ozone 2.8 mm Dust 300 particle/cc	
		Normal irradiation in watt/sq meter	Energy absorption in watt/sq meter
0	1.0000	933.338	914.615
5	1.0038	932.484	910.30
10	1.0154	929.900	897.393
15	1.0353	925.514	825.997
20	1.0642	919.202	846.287
25	1.1034	910.778	808.503
30	1.1547	899.975	762.952
35	1.2208	886.427	710.004
40	1.3054	869.623	650.093
45	1.4142	848.853	583.728
50	1.5557	823.111	511.518
55	1.7434	790.934	434.230
60	2.0000	750.126	352.930
65	2.3662	697.258	269.258
70	2.9238	626.740	185.988
75	3.8637	529.006	108.037
80	5.7588	387.171	43.958

Table VII—Continued

Zenith distance	Air mass	Pressure 785 mm of Hg Water vapor 30 mm precipitable Ozone 2.8 mm Dust 300 particle/cc	
		Normal irradiation in watt/sq meter	Energy absorption in watt/sq meter
0	1.0000	908.405	890.159
5	1.0038	907.530	885.917
10	1.0154	904.882	873.227
15	1.0353	900.385	852.191
20	1.0642	893.913	822.982
25	1.1034	885.269	785.838
30	1.1547	874.177	741.062
35	1.2208	860.252	689.020
40	1.3054	842.963	630.145
45	1.4142	821.571	564.949
50	1.5557	795.033	494.051
55	1.7434	761.854	418.247
60	2.0000	719.825	338.656
65	2.3662	665.588	257.009
70	2.9238	593.840	176.207
75	3.8637	495.889	101.258
80	5.7588	47.282	40.556

Table VII—Continued

Zenith distance	Air mass	Pressure 785 mm of Hg Water vapor 40 mm precipitable Ozone 2.8 mm Dust 300 particle/cc	
		Normal irradiation in watt/sq meter	Energy absorption in watt/sq meter
0	1.0000	888.611	870.747
5	1.0038	887.712	866.554
10	1.0154	884.989	854.014
15	1.0353	880.366	833.228
20	1.0642	873.709	804.367
25	1.1034	864.819	767.671
30	1.1547	853.408	723.442
35	1.2208	839.084	672.051
40	1.3054	821.305	613.941
45	1.4142	799.324	549.638
50	1.5557	772.105	449.789
55	1.7434	738.171	405.231
60	2.0000	695.385	327.142
65	2.3662	640.551	247.326
70	2.9238	568.722	168.739
75	3.8637	471.975	96.364
80	5.7588	337.571	38.313

Table VIII

AVERAGE RADIANCE FOR WRIGHT FIELD
UNITS IN WATTS/M^2 STERADIAN

Zenith distance (°)	Zenith angle (°)							
	10	20	30	40	50	60	70	80
17.5	39.91	40.21	33.66	30.46	27.57	26.12	23.60	21.11
27.5	26.96	38.06	38.47	34.03	25.48	28.98	25.30	22.60
37.0	35.67	37.62	28.69	37.46	34.53	32.63	29.40	26.27
47.0	32.70	32.11	34.29	36.43	36.18	32.47	29.54	25.57
57.0	32.44	32.68	32.59	32.19	35.50	34.68	31.46	28.89
66.0	31.60	31.51	31.38	32.57	32.66	33.52	32.54	29.32
76.5	31.58	31.39	31.77	31.86	31.32	30.40	31.28	30.90
86.5	28.91	27.88	27.14	26.27	25.70	23.68	21.37	21.11

AVERAGE RADIANCE FOR PIKES PEAK
UNITS IN WATTS/M^2 STERADIAN

Zenith distance (°)	Zenith angle (°)							
	10	20	30	40	50	60	70	80
36.0	7.72	9.59	11.22	11.47	8.83	7.99	6.74	9.54
38.5	10.71	11.73	7.52	7.87	7.41	6.09	5.97	5.90
44.5	6.01	7.30	7.39	8.93	8.93	7.02	6.37	6.93
47.0	3.88	4.60	5.82	8.79	10.13	6.49	5.90	6.86
54.5	2.92	4.06	4.89	6.03	7.44	7.17	7.74	9.26
55.0	2.61	3.23	3.46	4.67	7.54	7.90	6.70	6.93
63.0	2.79	3.09	3.47	4.57	5.49	8.64	8.80	8.89
67.5	2.04	2.83	4.36	4.86	7.80	8.82	9.70	12.28
73.0	2.66	3.82	3.59	4.59	5.44	6.58	9.42	11.37
76.0	0.92	1.87	2.98	5.77	7.89	7.60	9.87	13.27
79.0	1.72	2.42	3.11	3.99	4.89	5.11	8.56	14.11
86.0	0.49	1.03	1.90	3.08	4.37	4.32	6.58	8.31
90.0	1.38	2.12	2.64	3.40	4.07	3.81	4.77	6.71

Table VIII—Continued

AVERAGE RADIANCE FOR PETERSON FIELD
UNITS IN WATTS/M^2 STERADIAN

Zenith distance (°)	Zenith angle (°)							
	10	20	30	40	50	60	70	80
35.0	9.89	9.11	10.08	9.83	8.06	7.28	7.01	7.00
36.5	8.83	9.20	9.92	9.44	8.12	7.23	6.16	7.87
44.5	8.59	8.77	9.56	10.56	11.07	9.24	8.42	9.20
53.0	5.34	5.44	5.48	7.03	8.01	7.71	7.68	7.34
55.0	6.27	5.89	7.41	8.22	8.40	8.77	8.51	8.89
65.0	8.01	6.78	6.28	6.90	8.76	8.61	11.12	14.44
66.0	5.46	6.53	6.39	6.74	8.10	9.56	10.70	12.76
76.0	4.24	5.04	5.67	5.91	6.34	7.13	8.78	10.16
76.0	5.28	5.86	4.39	4.91	5.72	8.22	9.84	13.29
86.0	3.40	3.89	4.21	4.62	5.19	5.76	6.72	9.34
87.0	3.34	3.54	2.70	3.70	5.04	4.99	6.16	9.68

22, August 8, September 23, November 8, and December 22 were determined for each hour from sunrise to sunset. Plates of these values were prepared and then fit, using a Fourier series representation. It was found that the solar zenith angle could be represented within 10 percent by the following simple expression

$$z = 90.00 - A \sin \frac{\pi t}{\Delta t} \qquad \text{(IV-1)}$$

where

z is the zenith angle in degrees
A is a constant dependent on the location and date
t is the time from sunrise in hours
Δt is the time between sunrise and sunset.

The constant A in Equation (IV-1) is the difference between the solar zenith angle at local noon and 90°, i.e., $A = 90.0 - z_{noon}$. Values for A and Δt were determined from the 1966 Almanac for each date and for latitudes of 30^oN, 35^oN, and 40^oN.

Direct Solar Energy Input Determination.—The direct solar energy input to a horizontal water surface was determined from the tabulations of energy incident and absorbed given in Table VII. From Table VII, the values of irradiation and energy absorbed were given as a function of the solar zenith angle. These quantities are also cyclic and were represented by a Fourier series with the zenith angle as the dependent variable. It was necessary to use several terms of the Fourier series to represent these values. A typical expression for the energy absorbed was of the following form:

$$q''_{abs} = b_1 \cos z + b_3 \cos 3z + b_5 \cos 5z + b_7 \cos 7z \qquad \text{(IV-2)}$$

where

q''_{abs} is the energy absorbed per square foot per hour
b_1, b_3, b_5, b_7 are the Fourier coefficients
Z is the solar zenith angle.

A similar equation was used to represent the direct solar irradiation. By using Equations (IV-1) and (IV-2), the solar energy absorbed and incident on a horizontal water surface per day was evaluated. This was accomplished by integrating Equation (IV-2) with the zenith angle expressed from Equation (IV-1). Values for these quantities are tabulated in Table IX in Btu/ft^2–day.

Scattered Solar Energy Input.—Values of the solar energy scattered to a water surface by the atmosphere were obtained as explained previously. These values as a function of the solar zenith angle were expressed by the least square error method to obtain analytical expressions. Once again by using equation (IV-1), the values were integrated over a period of one day. Tabulated values of these quantities are presented in Table IX.

Thermal Energy Input.—The radiant energy input to a water surface from the atmosphere over the surface was obtained from the expressions presented by Bennett, et al. [21]. This was accomplished using the following equations:

$$\ln \frac{B}{B-S} = C_2 M_o^{1/2} \csc \theta^{1/2} \qquad \text{(IV-3)}$$

$$@\, \theta = \pi/2, S = S_z = E_z \sigma T^4_{amb} \qquad \text{(IV-4)}$$

$$1 - E_z = (1 - E_H)^{0.776} \qquad \text{(IV-5)}$$

$$E_H = a + b\, e^{1/2} \qquad \text{(IV-6)}$$

where

B is the radiance of a black body at T_{amb}
S is the incident radiance in watt/square meter-steradian
C_2 and M_o are constants
θ is the angular altitude or 90-zenith angle
T_{amb} is the ambient atmospheric temperature
σ is the Stefan Boltzmann constant
E_z is the vertical emittance of the atmosphere
a and b are constants
e is the partial pressure of the water in the atmosphere in mm of Hg.

Equations (IV-3) through (IV-6) can be solved for the incident radiance if the ambient atmospheric temperature and the partial pressure of the water vapor are known. Constants a and b were used as 0.52 and 0.065, as suggested by Bennett, et al. [21]. With the value of S known, the thermal energy incident on a horizontal surface was obtained by integration over the hemisphere above the surface (see discussion in Chapter III, Thermal Energy). This value was multiplied by 0.866, which represents the diffuse absorptance of a quiescent water surface for long wavelength radiant energy [22]. Values obtained in this manner are tabulated as a function of the ambient temperature and relative humidity in Table X.

Table IX

SOLAR ENERGY INPUT TO A LAKE.
Values in BTU/sq foot–day.

	DIRECT IRRADIATION	DIRECT ABSORBED	SCATTERED IRRADIATION	SCATTERED ABSORBED
LATITUDE 30 ELEVATION FT 1000 DATE 11/ 8 MM PRECIP WATER 10	1.174E 03	1.115E 03	3.275E 02	3.083E 02
LATITUDE 30 ELEVATION FT 1000 DATE 11/ 8 MM PRECIP WATER 20	1.114E 03	1.058E 03	3.275E 02	3.083E 02
LATITUDE 30 ELEVATION FT 1000 DATE 11/ 8 MM PRECIP WATER 30	1.071E 03	1.017E 03	3.275E 02	3.083E 02
LATITUDE 30 ELEVATION FT 1000 DATE 11/ 8 MM PRECIP WATER 40	1.037E 03	9.851E 02	3.275E 02	3.083E 02
LATITUDE 30 ELEVATION FT 1000 DATE 12/22 MM PRECIP WATER 10	9.082E 02	8.317E 02	3.032E 02	2.853E 02
LATITUDE 30 ELEVATION FT 1000 DATE 12/22 MM PRECIP WATER 20	8.561E 02	7.851E 02	3.032E 02	2.853E 02
LATITUDE 30 ELEVATION FT 1000 DATE 12/22 MM PRECIP WATER 30	8.185E 02	7.522E 02	3.032E 02	2.853E 02
LATITUDE 30 ELEVATION FT 1000 DATE 12/22 MM PRECIP WATER 40	7.897E 02	7.263E 02	3.032E 02	2.853E 02
LATITUDE 30 ELEVATION FT 1000 DATE 2/ 4 MM PRECIP WATER 10	1.185E 03	1.128E 03	3.272E 02	3.079E 02
LATITUDE 30 ELEVATION FT 1000 DATE 2/ 4 MM PRECIP WATER 20	1.126E 03	1.070E 03	3.272E 02	3.079E 02
LATITUDE 30 ELEVATION FT 1000 DATE 2/ 4 MM PRECIP WATER 30	1.082E 03	1.030E 03	3.272E 02	3.079E 02
LATITUDE 30 ELEVATION FT 1000 DATE 2/ 4 MM PRECIP WATER 40	1.048E 03	9.972E 02	3.272E 02	3.079E 02
LATITUDE 30 ELEVATION FT 1000 DATE 3/21 MM PRECIP WATER 10	1.873E 03	1.815E 03	3.695E 02	3.483E 02
LATITUDE 30 ELEVATION FT 1000 DATE 3/21 MM PRECIP WATER 20	1.788E 03	1.732E 03	3.695E 02	3.483E 02

Table IX—Continued

LATITUDE 30 ELEVATION FT 1000 DATE 3/21 MM PRECIP WATER 30	1.730E 03	1.675E 03	3.695E 02	3.483E 02
LATITUDE 30 ELEVATION FT 1000 DATE 3/21 MM PRECIP WATER 40	1.683E 03	1.630E 03	3.695E 02	3.483E 02
LATITUDE 30 ELEVATION FT 1000 DATE 5/ 6 MM PRECIP WATER 10	2.522E 03	2.430E 03	3.963E 02	3.743E 02
LATITUDE 30 ELEVATION FT 1000 DATE 5/ 6 MM PRECIP WATER 20	2.411E 03	2.326E 03	3.963E 02	3.743E 02
LATITUDE 30 ELEVATION FT 1000 DATE 5/ 6 MM PRECIP WATER 30	2.336E 03	2.255E 03	3.963E 02	3.743E 02
LATITUDE 30 ELEVATION FT 1000 DATE 5/ 6 MM PRECIP WATER 40	2.276E 03	2.199E 03	3.963E 02	3.743E 02
LATITUDE 30 ELEVATION FT 1000 DATE 6/22 MM PRECIP WATER 10	2.831E 03	2.747E 03	4.028E 02	3.811E 02
LATITUDE 30 ELEVATION FT 1000 DATE 6/22 MM PRECIP WATER 20	2.711E 03	2.632E 03	4.028E 02	3.811E 02
LATITUDE 30 ELEVATION FT 1000 DATE 6/22 MM PRECIP WATER 30	2.630E 03	2.554E 03	4.028E 02	3.811E 02
LATITUDE 30 ELEVATION FT 1000 DATE 6/22 MM PRECIP WATER 40	2.565E 03	2.492E 03	4.028E 02	3.811E 02
LATITUDE 30 ELEVATION FT 1000 DATE 8/ 8 MM PRECIP WATER 10	2.537E 03	2.446E 03	3.943E 02	3.725E 02
LATITUDE 30 ELEVATION FT 1000 DATE 8/ 8 MM PRECIP WATER 20	2.426E 03	2.341E 03	3.943E 02	3.725E 02
LATITUDE 30 ELEVATION FT 1000 DATE 8/ 8 MM PRECIP WATER 30	2.351E 03	2.270E 03	3.943E 02	3.725E 02
LATITUDE 30 ELEVATION FT 1000 DATE 8/ 8 MM PRECIP WATER 40	2.291E 03	2.214E 03	3.943E 02	3.725E 02

Table IX—Continued

LATITUDE 30 ELEVATION FT 1000 DATE 9/23 MM PRECIP WATER 10	1.859E 03	1.802E 03	3.690E 02	3.478E 02
LATITUDE 30 ELEVATION FT 1000 DATE 9/23 MM PRECIP WATER 20	1.775E 03	1.719E 03	3.690E 02	3.478E 02
LATITUDE 30 ELEVATION FT 1000 DATE 9/23 MM PRECIP WATER 30	1.717E 03	1.663E 03	3.690E 02	3.478E 02
LATITUDE 30 ELEVATION FT 1000 DATE 9/23 MM PRECIP WATER 40	1.670E 03	1.618E 03	3.690E 02	3.478E 02
LATITUDE 30 ELEVATION FT 5000 DATE 11/ 8 MM PRECIP WATER 10	1.203E 03	1.143E 03	7.731E 01	7.173E 01
LATITUDE 30 ELEVATION FT 5000 DATE 11/ 8 MM PRECIP WATER 20	1.143E 03	1.086E 03	7.731E 01	7.173E 01
LATITUDE 30 ELEVATION FT 5000 DATE 11/ 8 MM PRECIP WATER 30	1.101E 03	1.045E 03	7.731E 01	7.173E 01
LATITUDE 30 ELEVATION FT 5000 DATE 11/ 8 MM PRECIP WATER 40	1.066E 03	1.013E 03	7.731E 01	7.173E 01
LATITUDE 30 ELEVATION FT 5000 DATE 12/22 MM PRECIP WATER 10	9.340E 02	8.548E 02	7.025E 01	6.486E 01
LATITUDE 30 ELEVATION FT 5000 DATE 12/22 MM PRECIP WATER 20	8.812E 02	8.080E 02	7.025E 01	6.486E 01
LATITUDE 30 ELEVATION FT 5000 DATE 12/22 MM PRECIP WATER 30	8.442E 02	7.752E 02	7.025E 01	6.486E 01
LATITUDE 30 ELEVATION FT 5000 DATE 12/22 MM PRECIP WATER 40	8.152E 02	7.490E 02	7.025E 01	6.486E 01
LATITUDE 30 ELEVATION FT 5000 DATE 2/ 4 MM PRECIP WATER 10	1.215E 03	1.156E 03	7.731E 01	7.176E 01
LATITUDE 30 ELEVATION FT 5000 DATE 2/ 4 MM PRECIP WATER 20	1.154E 03	1.098E 03	7.731E 01	7.176E 01

Table IX—Continued

LATITUDE 30 ELEVATION FT 5000 DATE 2/ 4 MM PRECIP WATER 30	1.112E 03	1.058E 03	7.731E 01	7.176E 01
LATITUDE 30 ELEVATION FT 5000 DATE 2/ 4 MM PRECIP WATER 40	1.078E 03	1.025E 03	7.731E 01	7.176E 01
LATITUDE 30 ELEVATION FT 5000 DATE 3/21 MM PRECIP WATER 10	1.913E 03	1.853E 03	8.979E 01	8.480E 01
LATITUDE 30 ELEVATION FT 5000 DATE 3/21 MM PRECIP WATER 20	1.827E 03	1.770E 03	8.979E 01	8.480E 01
LATITUDE 30 ELEVATION FT 5000 DATE 3/21 MM PRECIP WATER 30	1.769E 03	1.713E 03	8.979E 01	8.480E 01
LATITUDE 30 ELEVATION FT 5000 DATE 3/21 MM PRECIP WATER 40	1.722E 03	1.668E 03	8.979E 01	8.480E 01
LATITUDE 30 ELEVATION FT 5000 DATE 5/ 6 MM PRECIP WATER 10	2.572E 03	2.476E 03	9.702E 01	9.376E 01
LATITUDE 30 ELEVATION FT 5000 DATE 5/ 6 MM PRECIP WATER 20	2.460E 03	2.372E 03	9.702E 01	9.376E 01
LATITUDE 30 ELEVATION FT 5000 DATE 5/ 6 MM PRECIP WATER 30	2.385E 03	2.301E 03	9.702E 01	9.376E 01
LATITUDE 30 ELEVATION FT 5000 DATE 5/ 6 MM PRECIP WATER 40	2.325E 03	2.244E 03	9.702E 01	9.376E 01
LATITUDE 30 ELEVATION FT 5000 DATE 6/22 MM PRECIP WATER 10	2.883E 03	2.798E 03	9.832E 01	9.665E 01
LATITUDE 30 ELEVATION FT 5000 DATE 6/22 MM PRECIP WATER 20	2.763E 03	2.682E 03	9.832E 01	9.665E 01
LATITUDE 30 ELEVATION FT 5000 DATE 6/22 MM PRECIP WATER 30	2.682E 03	2.604E 03	9.832E 01	9.665E 01
LATITUDE 30 ELEVATION FT 5000 DATE 6/22 MM PRECIP WATER 40	2.618E 03	2.542E 03	9.832E 01	9.665E 01

Table IX—Continued

LATITUDE 30 ELEVATION FT 5000 DATE 8/ 8 MM PRECIP WATER 10	2.587E 03	2.492E 03	9.651E 01	9.343E 01
LATITUDE 30 ELEVATION FT 5000 DATE 8/ 8 MM PRECIP WATER 20	2.475E 03	2.387E 03	9.651E 01	9.343E 01
LATITUDE 30 ELEVATION FT 5000 DATE 8/ 8 MM PRECIP WATER 30	2.400E 03	2.316E 03	9.651E 01	9.343E 01
LATITUDE 30 ELEVATION FT 5000 DATE 8/ 8 MM PRECIP WATER 40	2.340E 03	2.260E 03	9.651E 01	9.343E 01
LATITUDE 30 ELEVATION FT 5000 DATE 9/23 MM PRECIP WATER 10	1.899E 03	1.840E 03	8.963E 01	8.462E 01
LATITUDE 30 ELEVATION FT 5000 DATE 9/23 MM PRECIP WATER 20	1.814E 03	1.757E 03	8.963E 01	8.462E 01
LATITUDE 30 ELEVATION FT 5000 DATE 9/23 MM PRECIP WATER 30	1.756E 03	1.701E 03	8.963E 01	8.462E 01
LATITUDE 30 ELEVATION FT 5000 DATE 9/23 MM PRECIP WATER 40	1.709E 03	1.655E 03	8.963E 01	8.462E 01
LATITUDE 35 ELEVATION FT 1000 DATE 11/ 8 MM PRECIP WATER 10	9.969E 02	9.227E 02	3.166E 02	2.979E 02
LATITUDE 35 ELEVATION FT 1000 DATE 11/ 8 MM PRECIP WATER 20	9.416E 02	8.722E 02	3.166E 02	2.979E 02
LATITUDE 35 ELEVATION FT 1000 DATE 11/ 8 MM PRECIP WATER 30	9.017E 02	8.366E 02	3.166E 02	2.979E 02
LATITUDE 35 ELEVATION FT 1000 DATE 11/ 8 MM PRECIP WATER 40	8.708E 02	8.085E 02	3.166E 02	2.979E 02
LATITUDE 35 ELEVATION FT 1000 DATE 12/22 MM PRECIP WATER 10	7.252E 02	6.434E 02	2.866E 02	2.697E 02
LATITUDE 35 ELEVATION FT 1000 DATE 12/22 MM PRECIP WATER 20	6.791E 02	6.044E 02	2.866E 02	2.697E 02

Table IX—Continued

LATITUDE 35 ELEVATION FT 1000 DATE 12/22 MM PRECIP WATER 30	6.461E 02	5.768E 02	2.866E 02	2.697E 02
LATITUDE 35 ELEVATION FT 1000 DATE 12/22 MM PRECIP WATER 40	6.214E 02	5.555E 02	2.866E 02	2.697E 02
LATITUDE 35 ELEVATION FT 1000 DATE 2/ 4 MM PRECIP WATER 10	1.378E 03	1.336E 03	3.220E 02	3.032E 02
LATITUDE 35 ELEVATION FT 1000 DATE 2/ 4 MM PRECIP WATER 20	1.314E 03	1.272E 03	3.220E 02	3.032E 02
LATITUDE 35 ELEVATION FT 1000 DATE 2/ 4 MM PRECIP WATER 30	1.268E 03	1.228E 03	3.220E 02	3.032E 02
LATITUDE 35 ELEVATION FT 1000 DATE 2/ 4 MM PRECIP WATER 40	1.232E 03	1.192E 03	3.220E 02	3.032E 02
LATITUDE 35 ELEVATION FT 1000 DATE 3/21 MM PRECIP WATER 10	1.714E 03	1.665E 03	3.704E 02	3.490E 02
LATITUDE 35 ELEVATION FT 1000 DATE 3/21 MM PRECIP WATER 20	1.635E 03	1.587E 03	3.704E 02	3.490E 02
LATITUDE 35 ELEVATION FT 1000 DATE 3/21 MM PRECIP WATER 30	1.580E 03	1.533E 03	3.704E 02	3.490E 02
LATITUDE 35 ELEVATION FT 1000 DATE 3/21 MM PRECIP WATER 40	1.536E 03	1.490E 03	3.704E 02	3.490E 02
LATITUDE 35 ELEVATION FT 1000 DATE 5/ 6 MM PRECIP WATER 10	2.449E 03	2.357E 03	4.096E 02	3.866E 02
LATITUDE 35 ELEVATION FT 1000 DATE 5/ 6 MM PRECIP WATER 20	2.339E 03	2.254E 03	4.096E 02	3.866E 02
LATITUDE 35 ELEVATION FT 1000 DATE 5/ 6 MM PRECIP WATER 30	2.265E 03	2.184E 03	4.096E 02	3.866E 02
LATITUDE 35 ELEVATION FT 1000 DATE 5/ 6 MM PRECIP WATER 40	2.206E 03	2.129E 03	4.096E 02	3.866E 02

Table IX—Continued

LATITUDE 35 ELEVATION FT 1000 DATE 6/22 MM PRECIP WATER 10	2.803E 03	2.707E 03	4.231E 02	3.998E 02
LATITUDE 35 ELEVATION FT 1000 DATE 6/22 MM PRECIP WATER 20	2.682E 03	2.592E 03	4.231E 02	3.998E 02
LATITUDE 35 ELEVATION FT 1000 DATE 6/22 MM PRECIP WATER 30	2.599E 03	2.514E 03	4.231E 02	3.998E 02
LATITUDE 35 ELEVATION FT 1000 DATE 6/22 MM PRECIP WATER 40	2.534E 03	2.452E 03	4.231E 02	3.998E 02
LATITUDE 35 ELEVATION FT 1000 DATE 8/ 8 MM PRECIP WATER 10	2.463E 03	2.370E 03	4.091E 02	3.861E 02
LATITUDE 35 ELEVATION FT 1000 DATE 8/ 8 MM PRECIP WATER 20	2.353E 03	2.267E 03	4.091E 02	3.861E 02
LATITUDE 35 ELEVATION FT 1000 DATE 8/ 8 MM PRECIP WATER 30	2.278E 03	2.197E 03	4.091E 02	3.861E 02
LATITUDE 35 ELEVATION FT 1000 DATE 8/ 8 MM PRECIP WATER 40	2.219E 03	2.141E 03	4.091E 02	3.861E 02
LATITUDE 35 ELEVATION FT 1000 DATE 9/23 MM PRECIP WATER 10	1.698E 03	1.649E 03	3.698E 02	3.484E 02
LATITUDE 35 ELEVATION FT 1000 DATE 9/23 MM PRECIP WATER 20	1.620E 03	1.572E 03	3.698E 02	3.484E 02
LATITUDE 35 ELEVATION FT 1000 DATE 9/23 MM PRECIP WATER 30	1.566E 03	1.518E 03	3.698E 02	3.484E 02
LATITUDE 35 ELEVATION FT 1000 DATE 9/23 MM PRECIP WATER 40	1.522E 03	1.475E 03	3.698E 02	3.484E 02
LATITUDE 35 ELEVATION FT 5000 DATE 11/ 8 MM PRECIP WATER 10	1.024E 03	9.476E 02	7.373E 01	6.815E 01
LATITUDE 35 ELEVATION FT 5000 DATE 11/ 8 MM PRECIP WATER 20	9.682E 02	8.969E 02	7.373E 01	6.815E 01

Table IX—Continued

LATITUDE 35 ELEVATION FT 5000 DATE 11/ 8 MM PRECIP WATER 30	9.289E 02	8.614E 02	7.373E 01	6.815E 01
LATITUDE 35 ELEVATION FT 5000 DATE 11/ 8 MM PRECIP WATER 40	8.979E 02	8.329E 02	7.373E 01	6.815E 01
LATITUDE 35 ELEVATION FT 5000 DATE 12/22 MM PRECIP WATER 10	7.479E 02	6.628E 02	6.528E 01	6.009E 01
LATITUDE 35 ELEVATION FT 5000 DATE 12/22 MM PRECIP WATER 20	7.012E 02	6.236E 02	6.528E 01	6.009E 01
LATITUDE 35 ELEVATION FT 5000 DATE 12/22 MM PRECIP WATER 30	6.687E 02	5.961E 02	6.528E 01	6.009E 01
LATITUDE 35 ELEVATION FT 5000 DATE 12/22 MM PRECIP WATER 40	6.439E 02	5.745E 02	6.528E 01	6.009E 01
LATITUDE 35 ELEVATION FT 5000 DATE 2/ 4 MM PRECIP WATER 10	1.409E 03	1.367E 03	7.727E 01	7.224E 01
LATITUDE 35 ELEVATION FT 5000 DATE 2/ 4 MM PRECIP WATER 20	1.344E 03	1.303E 03	7.727E 01	7.224E 01
LATITUDE 35 ELEVATION FT 5000 DATE 2/ 4 MM PRECIP WATER 30	1.299E 03	1.258E 03	7.727E 01	7.224E 01
LATITUDE 35 ELEVATION FT 5000 DATE 2/ 4 MM PRECIP WATER 40	1.262E 03	1.222E 03	7.727E 01	7.224E 01
LATITUDE 35 ELEVATION FT 5000 DATE 3/21 MM PRECIP WATER 10	1.751E 03	1.701E 03	8.945E 01	8.398E 01
LATITUDE 35 ELEVATION FT 5000 DATE 3/21 MM PRECIP WATER 20	1.672E 03	1.623E 03	8.945E 01	8.398E 01
LATITUDE 35 ELEVATION FT 5000 DATE 3/21 MM PRECIP WATER 30	1.617E 03	1.569E 03	8.945E 01	8.398E 01
LATITUDE 35 ELEVATION FT 5000 DATE 3/21 MM PRECIP WATER 40	1.573E 03	1.526E 03	8.945E 01	8.398E 01

Table IX—Continued

LATITUDE 35 ELEVATION FT 5000 DATE 5/ 6 MM PRECIP WATER 10	2.498E 03	2.403E 03	1.002E 02	9.608E 01
LATITUDE 35 ELEVATION FT 5000 DATE 5/ 6 MM PRECIP WATER 20	2.388E 03	2.300E 03	1.002E 02	9.608E 01
LATITUDE 35 ELEVATION FT 5000 DATE 5/ 6 MM PRECIP WATER 30	2.314E 03	2.230E 03	1.002E 02	9.608E 01
LATITUDE 35 ELEVATION FT 5000 DATE 5/ 6 MM PRECIP WATER 40	2.255E 03	2.174E 03	1.002E 02	9.608E 01
LATITUDE 35 ELEVATION FT 5000 DATE 6/22 MM PRECIP WATER 10	2.857E 03	2.758E 03	1.035E 02	1.007E 02
LATITUDE 35 ELEVATION FT 5000 DATE 6/22 MM PRECIP WATER 20	2.735E 03	2.643E 03	1.035E 02	1.007E 02
LATITUDE 35 ELEVATION FT 5000 DATE 6/22 MM PRECIP WATER 30	2.653E 03	2.565E 03	1.035E 02	1.007E 02
LATITUDE 35 ELEVATION FT 5000 DATE 6/22 MM PRECIP WATER 40	2.588E 03	2.502E 03	1.035E 02	1.007E 02
LATITUDE 35 ELEVATION FT 5000 DATE 8/ 8 MM PRECIP WATER 10	2.512E 03	2.416E 03	1.001E 02	9.605E 01
LATITUDE 35 ELEVATION FT 5000 DATE 8/ 8 MM PRECIP WATER 20	2.402E 03	2.313E 03	1.001E 02	9.605E 01
LATITUDE 35 ELEVATION FT 5000 DATE 8/ 8 MM PRECIP WATER 30	2.327E 03	2.243E 03	1.001E 02	9.605E 01
LATITUDE 35 ELEVATION FT 5000 DATE 8/ 8 MM PRECIP WATER 40	2.268E 03	2.187E 03	1.001E 02	9.605E 01
LATITUDE 35 ELEVATION FT 5000 DATE 9/23 MM PRECIP WATER 10	1.735E 03	1.686E 03	8.926E 01	8.375E 01
LATITUDE 35 ELEVATION FT 5000 DATE 9/23 MM PRECIP WATER 20	1.657E 03	1.608E 03	8.926E 01	8.375E 01

Table IX—Continued

LATITUDE 35 ELEVATION FT 5000 DATE 9/23 MM PRECIP WATER 30	1.602E 03	1.555E 03	8.926E 01	8.375E 01
LATITUDE 35 ELEVATION FT 5000 DATE 9/23 MM PRECIP WATER 40	1.558E 03	1.511E 03	8.926E 01	8.375E 01
LATITUDE 40 ELEVATION FT 1000 DATE 11/ 9 MM PRECIP WATER 10	8.167E 02	7.323E 02	3.031E 02	2.852E 02
LATITUDE 40 ELEVATION FT 1000 DATE 11/ 8 MM PRECIP WATER 20	7.666E 02	6.892E 02	3.031E 02	2.852E 02
LATITUDE 40 ELEVATION FT 1000 DATE 11/ 8 MM PRECIP WATER 30	7.306E 02	6.588E 02	3.031E 02	2.852E 02
LATITUDE 40 ELEVATION FT 1000 DATE 11/ 8 MM PRECIP WATER 40	7.035E 02	6.350E 02	3.031E 02	2.852E 02
LATITUDE 40 ELEVATION FT 1000 DATE 12/22 MM PRECIP WATER 10	5.429E 02	4.707E 02	2.673E 02	2.515E 02
LATITUDE 40 ELEVATION FT 1000 DATE 12/22 MM PRECIP WATER 20	5.049E 02	4.393E 02	2.673E 02	2.515E 02
LATITUDE 40 ELEVATION FT 1000 DATE 12/22 MM PRECIP WATER 30	4.778E 02	4.172E 02	2.673E 02	2.515E 02
LATITUDE 40 ELEVATION FT 1000 DATE 12/22 MM PRECIP WATER 40	4.580E 02	4.005E 02	2.673E 02	2.515E 02
LATITUDE 40 ELEVATION FT 1000 DATE 2/ 4 MM PRECIP WATER 10	8.286E 02	7.452E 02	3.027E 02	2.848E 02
LATITUDE 40 ELEVATION FT 1000 DATE 2/ 4 MM PRECIP WATER 20	7.783E 02	7.016E 02	3.027E 02	2.848E 02
LATITUDE 40 ELEVATION FT 1000 DATE 2/ 4 MM PRECIP WATER 30	7.421E 02	6.709E 02	3.027E 02	2.848E 02
LATITUDE 40 ELEVATION FT 1000 DATE 2/ 4 MM PRECIP WATER 40	7.147E 02	6.469E 02	3.027E 02	2.848E 02

Table IX—Continued

LATITUDE 40 ELEVATION FT 1000 DATE 3/21 MM PRECIP WATER 10	1.549E 03	1.500E 03	3.699E 02	3.483E 02
LATITUDE 40 ELEVATION FT 1000 DATE 3/21 MM PRECIP WATER 20	1.476E 03	1.428E 03	3.699E 02	3.483E 02
LATITUDE 40 ELEVATION FT 1000 DATE 3/21 MM PRECIP WATER 30	1.425E 03	1.377E 03	3.699E 02	3.483E 02
LATITUDE 40 ELEVATION FT 1000 DATE 3/21 MM PRECIP WATER 40	1.383E 03	1.337E 03	3.699E 02	3.483E 02
LATITUDE 40 ELEVATION FT 1000 DATE 5/ 6 MM PRECIP WATER 10	2.359E 03	2.274E 03	4.237E 02	3.996E 02
LATITUDE 40 ELEVATION FT 1000 DATE 5/ 6 MM PRECIP WATER 20	2.252E 03	2.173E 03	4.237E 02	3.996E 02
LATITUDE 40 ELEVATION FT 1000 DATE 5/ 6 MM PRECIP WATER 30	2.180E 03	2.104E 03	4.237E 02	3.996E 02
LATITUDE 40 ELEVATION FT 1000 DATE 5/ 6 MM PRECIP WATER 40	2.122E 03	2.049E 03	4.237E 02	3.996E 02
LATITUDE 40 ELEVATION FT 1000 DATE 6/22 MM PRECIP WATER 10	2.776E 03	2.674E 03	4.468E 02	4.219E 02
LATITUDE 40 ELEVATION FT 1000 DATE 6/22 MM PRECIP WATER 20	2.655E 03	2.559E 03	4.468E 02	4.219E 02
LATITUDE 40 ELEVATION FT 1000 DATE 6/22 MM PRECIP WATER 30	2.571E 03	2.461E 03	4.468E 02	4.219E 02
LATITUDE 40 ELEVATION FT 1000 DATE 6/22 MM PRECIP WATER 40	2.505E 03	2.418E 03	4.468E 02	4.219E 02
LATITUDE 40 ELEVATION FT 1000 DATE 8/ 8 MM PRECIP WATER 10	2.362E 03	2.278E 03	4.226E 02	3.986E 02
LATITUDE 40 ELEVATION FT 1000 DATE 8/ 8 MM PRECIP WATER 20	2.256E 03	2.177E 03	4.226E 02	3.986E 02

Table IX—Continued

LATITUDE 40 ELEVATION FT 1000 DATE 8/ 8 MM PRECIP WATER 30	2.183E 03	2.108E 03	4.226E 02	3.986E 02
LATITUDE 40 ELEVATION FT 1000 DATE 8/ 8 MM PRECIP WATER 40	2.125E 03	2.053E 03	4.226E 02	3.986E 02
LATITUDE 40 ELEVATION FT 1000 DATE 9/23 MM PRECIP WATER 10	1.534E 03	1.485E 03	3.692E 02	3.476E 02
LATITUDE 40 ELEVATION FT 1000 DATE 9/23 MM PRECIP WATER 20	1.461E 03	1.413E 03	3.692E 02	3.476E 02
LATITUDE 40 ELEVATION FT 1000 DATE 9/23 MM PRECIP WATER 30	1.410E 03	1.362E 03	3.692E 02	3.476E 02
LATITUDE 40 ELEVATION FT 1000 DATE 9/23 MM PRECIP WATER 40	1.369E 03	1.322E 03	3.692E 02	3.476E 02
LATITUDE 40 ELEVATION FT 5000 DATE 11/ 8 MM PRECIP WATER 10	8.414E 02	7.537E 02	6.947E 01	6.400E 01
LATITUDE 40 ELEVATION FT 5000 DATE 11/ 8 MM PRECIP WATER 20	7.906E 02	7.104E 02	6.947E 01	6.400E 01
LATITUDE 40 ELEVATION FT 5000 DATE 11/ 8 MM PRECIP WATER 30	7.552E 02	6.801E 02	6.947E 01	6.400E 01
LATITUDE 40 ELEVATION FT 5000 DATE 11/ 8 MM PRECIP WATER 40	7.279E 02	6.560E 02	6.947E 01	6.400E 01
LATITUDE 40 ELEVATION FT 5000 DATE 12/22 MM PRECIP WATER 10	5.615E 02	4.862E 02	5.964E 01	5.475E 01
LATITUDE 40 ELEVATION FT 5000 DATE 12/22 MM PRECIP WATER 20	5.229E 02	4.547E 02	5.964E 01	5.475E 01
LATITUDE 40 ELEVATION FT 5000 DATE 12/22 MM PRECIP WATER 30	4.964E 02	4.327E 02	5.964E 01	5.475E 01
LATITUDE 40 ELEVATION FT 5000 DATE 12/22 MM PRECIP WATER 40	4.765E 02	4.157E 02	5.964E 01	5.475E 01

Table IX—Continued

LATITUDE 40 ELEVATION FT 5000 DATE 2/ 4 MM PRECIP WATER 10	8.534E 02	7.668E 02	6.948E 01	6.403E 01
LATITUDE 40 ELEVATION FT 5000 DATE 2/ 4 MM PRECIP WATER 20	8.024E 02	7.230E 02	6.948E 01	6.403E 01
LATITUDE 40 ELEVATION FT 5000 DATE 2/ 4 MM PRECIP WATER 30	7.668E 02	6.924E 02	6.948E 01	6.403E 01
LATITUDE 40 ELEVATION FT 5000 DATE 2/ 4 MM PRECIP WATER 40	7.393E 02	6.681E 02	6.948E 01	6.403E 01
LATITUDE 40 ELEVATION FT 5000 DATE 3/21 MM PRECIP WATER 10	1.584E 03	1.535E 03	8.860E 01	8.274E 01
LATITUDE 40 ELEVATION FT 5000 DATE 3/21 MM PRECIP WATER 20	1.511E 03	1.462E 03	8.860E 01	8.274E 01
LATITUDE 40 ELEVATION FT 5000 DATE 3/21 MM PRECIP WATER 30	1.460E 03	1.412E 03	8.860E 01	8.274E 01
LATITUDE 40 ELEVATION FT 5000 DATE 3/21 MM PRECIP WATER 40	1.418E 03	1.371E 03	8.860E 01	8.274E 01
LATITUDE 40 ELEVATION FT 5000 DATE 5/ 6 MM PRECIP WATER 10	2.407E 03	2.320E 03	1.034E 02	9.843E 01
LATITUDE 40 ELEVATION FT 5000 DATE 5/ 6 MM PRECIP WATER 20	2.300E 03	2.219E 03	1.034E 02	9.843E 01
LATITUDE 40 ELEVATION FT 5000 DATE 5/ 6 MM PRECIP WATER 30	2.228E 03	2.150E 03	1.034E 02	9.843E 01
LATITUDE 40 ELEVATION FT 5000 DATE 5/ 6 MM PRECIP WATER 40	2.170E 03	2.095E 03	1.034E 02	9.843E 01
LATITUDE 40 ELEVATION FT 5000 DATE 6/22 MM PRECIP WATER 10	2.833E 03	2.726E 03	1.094E 02	1.054E 02
LATITUDE 40 ELEVATION FT 5000 DATE 6/22 MM PRECIP WATER 20	2.709E 03	2.610E 03	1.094E 02	1.054E 02

Table IX—Continued

LATITUDE 40 ELEVATION FT 5000 DATE 6/22 MM PRECIP WATER 30	2.626E 03	2.532E 03	1.094E 02	1.054E 02
LATITUDE 40 ELEVATION FT 5000 DATE 6/22 MM PRECIP WATER 40	2.560E 03	2.469E 03	1.094E 02	1.054E 02
LATITUDE 40 ELEVATION FT 5000 DATE 8/ 8 MM PRECIP WATER 10	2.411E 03	2.323E 03	1.032E 02	9.823E 01
LATITUDE 40 ELEVATION FT 5000 DATE 8/ 8 MM PRECIP WATER 20	2.304E 03	2.222E 03	1.032E 02	9.823E 01
LATITUDE 40 ELEVATION FT 5000 DATE 8/ 8 MM PRECIP WATER 30	2.231E 03	2.153E 03	1.032E 02	9.823E 01
LATITUDE 40 ELEVATION FT 5000 DATE 8/ 8 MM PRECIP WATER 40	2.173E 03	2.098E 03	1.032E 02	9.823E 01
LATITUDE 40 ELEVATION FT 5000 DATE 9/23 MM PRECIP WATER 10	1.569E 03	1.519E 03	8.837E 01	8.249E 01
LATITUDE 40 ELEVATION FT 5000 DATE 9/23 MM PRECIP WATER 20	1.496E 03	1.447E 03	8.837E 01	8.249E 01
LATITUDE 40 ELEVATION FT 5000 DATE 9/23 MM PRECIP WATER 30	1.445E 03	1.397E 03	8.837E 01	8.249E 01
LATITUDE 40 ELEVATION FT 5000 DATE 9/23 MM PRECIP WATER 40	1.403E 03	1.356E 03	8.837E 01	8.249E 01

Table X

THERMAL ENERGY INPUT TO A LAKE.
Values in BTU/hour—sq ft.

TEMP DEGREES F	HUMIDITY 0	10	20	30	40	50	60	70	80	90	100
20.0	40.94	43.49	44.55	45.36	46.04	46.64	47.19	47.69	48.15	48.59	49.00
30.0	44.45	47.96	49.42	50.53	51.47	52.29	53.04	53.72	54.36	54.96	55.53
40.0	48.20	52.87	54.80	56.28	57.52	58.62	59.61	60.53	61.37	62.17	62.93
50.0	52.17	58.28	60.81	62.74	64.37	65.81	67.11	68.30	69.42	70.46	71.45
60.0	56.38	64.30	67.58	70.09	72.20	74.06	75.75	77.29	78.74	80.09	81.37
70.0	60.85	71.02	75.22	78.44	81.16	83.55	85.71	87.70	89.56	91.30	92.96
80.0	65.57	78.52	83.86	87.96	91.42	94.47	97.23	99.78	102.15	104.38	106.51
90.0	70.56	86.91	93.66	98.84	103.21	107.07	110.58	113.81	116.84	119.71	122.44
100.0	75.84	96.31	104.77	111.27	116.77	121.63	126.07	130.19	134.08	137.83	141.52
110.0	81.40	106.86	117.39	125.49	132.37	138.51	144.16	149.53	154.96	156.59	156.59
120.0	87.27	118.70	131.72	141.79	150.41	158.24	165.91	167.88	167.88	167.88	167.88
130.0	93.44	132.01	148.03	160.53	171.49	179.76	179.76	179.76	179.76	179.76	179.76

Suggested Energy Budget Technique

The suggested technique to be used in the evaluation of the radiant energy input to a lake will be described in the following:

Determination of Climatalogy Parameters.—The basic climatalogical parameters required to determine the radiant energy input should be obtained from the National Weather Records Office in Asheville, North Carolina. Data from each of the major weather stations around the country are collected and recorded in this office.

Climatalogy parameters required for this evaluation are precipitable water in the atmosphere, hours of sunshine, atmospheric temperature, relative humidity and, if available, hours of overcast sky. These parameters, on an average basis, are required for each of the significant dates of a year. These dates are February 4, March 21, May 6, June 22, August 8, September 23, November 8, and December 22. Average values of the climatology records for these dates should represent the averages over the seasons.

Evaluation of Direct Solar Input.—The direct solar energy input can be determined from the latitude, millimeters of precipitable water and elevation of the storage site. Values of energy input per day given in Table IX are based on a clear day. In order to consider a day during which the number of hours of sunshine are less than the number of hours between sunrise and sunset, the tabulated values should be reduced by the ratio (hours of sunshine/hours between sunrise and sunset). See Table XI for the hours between sunrise and sunset. By doing this for each date tabulated, the average direct solar input per day can be found.

Table XI

HOURS BETWEEN SUNRISE AND SUNSET

	30° N	35° N	40° N
November 8	10.85	10.6	10.3
December 22	10.2	9.8	9.33
February 4	10.83	10.57	12.27
March 21	12.15	12.15	12.15
May 6	13.43	13.7	14.03
June 22	14.1	14.5	15.06
August 8	13.4	13.7	14.0
September 23	12.13	12.13	12.13

Evaluation of Scattered Solar Input.—Scattered solar input is primarily dependent upon the elevation of the storage site. From the elevation and Table IX, the average daily input can be evaluated. Once again, these values are based on a clear sky and should be adjusted for the daily average cloud cover. Ideally, this would be done by multiplying by the ratio (hours of overcast sky/hours between sunrise and sunset); however, data for the hours of overcast sky may not be available. In the absence of such data, the ratio used to determine the direct solar input can be used.

Evaluation of Thermal Energy Input.—The thermal energy input depends on the atmospheric temperature and relative humidity. From climatology records for the storage site, the hourly atmospheric temperature or daylight and night averages are required. If hourly values are available for temperature and relative humidity, energy input in Btu/ft^2—hour are obtained from Table X. These values must be summed to obtain energy input per day as obtained from the previous tabulations. The reason for the unit change in the table was to allow for diurnal variations as explained previously.

CHAPTER V. ANALYTICAL STUDY OF INFLUENCE OF SOLAR RADIATION REFLECTANCE ON WATER EVAPORATION

Background

The purpose of this part of the study was to investigate analytically the effect film reflectance of solar energy has on water evaporation. Analytical results show how ideal chemical films with different reflectance properties influence the amount of evaporation.

A great deal of work has been done since Dalton first established relationship for the evaporation process. Dalton's equation states that:

$$E = K_e U(P_S - P_a) \qquad \text{(V-1)}$$

where

K_e = a lumped constant influenced by air conditions
U = wind velocity
P_S = saturated vapor pressure at water surface temperature
P_a = partial vapor pressure at air temperature
E = evaporation.

Many investigators [24, 25, 26, 27] have attempted to determine analytical and experimental techniques for conveniently predicting evaporative loss and the various parameters which influence it.

One investigator made a steady-state assumption and showed that the daily convective heat transfer should be proportional to the evaporation rate [28]. This ratio was later called the Bowen ratio and is written as follows:

$$R_B = C \frac{t_S - t_a}{P_S - P_a} \frac{P}{760} \qquad \text{(V-2)}$$

where

t_S = water surface temperature
t_a = air temperature
P_S = saturated vapor pressure of water surface
P_a = vapor pressure of air
P = atmospheric pressure
C = a constant.

Other investigators have developed models based on assumptions of particular types of airflow over the water surface [29, 30] and upon form of the radiant energy exchange between the sun and the water and between the sky and the water [31, 32].

As part of a report for the U.S. Geological Survey [33], Anderson performed extensive work on the energy-budget method for determining evaporation at Lake Hefner in Oklahoma City, Oklahoma. Anderson used the following energy-budget equation in determining lake evaporation:

$$Q_s - Q_r - Q_b - Q_h - Q_e + Q_{v'} = Q_\rho \qquad \text{(V-3)}$$

where

Q_s = solar radiation incident on water surface
Q_r = reflected solar radiation
Q_b = net long-wave energy exchange
Q_h = energy convected from the body of water to the atmosphere
Q_e = energy utilized for evaporation
$Q_{v'}$ = net energy advected into the body of water
Q_ρ = the increase in energy stored in the body of water.

Various techniques were used to evaluate the above terms that influence evaporation.

The report concluded that the energy-budget method for determining evaporation is valid provided that energy storage terms are considered. In addition, the report indicated that for purposes of evaporation determination empirical evaluations are inadequate for atmospheric radiation, and considerable controversy still exists over the meaning and validity of Bowen's ratio.

Further evaporation studies have been reported for work at Lake Mead [34] and Lake Erie [35].

It has been well established that certain monomolecular films applied to water surfaces will retard evaporation. Also, it has been shown that if films with certain optical properties are available, they should significantly increase the reflectance of solar energy [36]. If the net radiant energy input to a body of water is reduced, then the evaporation will also be reduced, as will be shown in the following paragraphs.

Analytical Model

An analytical model was developed for determining the daily evaporation rate from a water surface under two different conditions. The first condition assumed the water surface to behave in a typical fashion. The second condition assumed that the water surface was covered by various hypothetical films having optical properties which result in increased solar energy reflectance. In addition, the films were considered to have the diffusion properties of a cetyl alcohol monolayer (to act as a diffusion barrier).

The model considered that an element of a typical water reservoir undergoes transient energy exchange resulting from the variation of radiation, convection and evaporation heat transfer with the time of day. It was assumed that the water element behaved as a slab undergoing conduction, when the water temperature decreases with depth (no buoyancy effects) and that it behaves as a mixing medium undergoing free convection heat exchange when temperature increases with depth (buoyancy effects).

As shown in Figure 17, the element of water was divided into various subvolumes or nodes. This was done so that the conduction equation:

$$\frac{\partial t}{\partial \theta} = a \frac{\partial^2 t}{\partial z^2} \qquad \text{(V-4)}$$

could be solved numerically by standard techniques [37], as illustrated below.

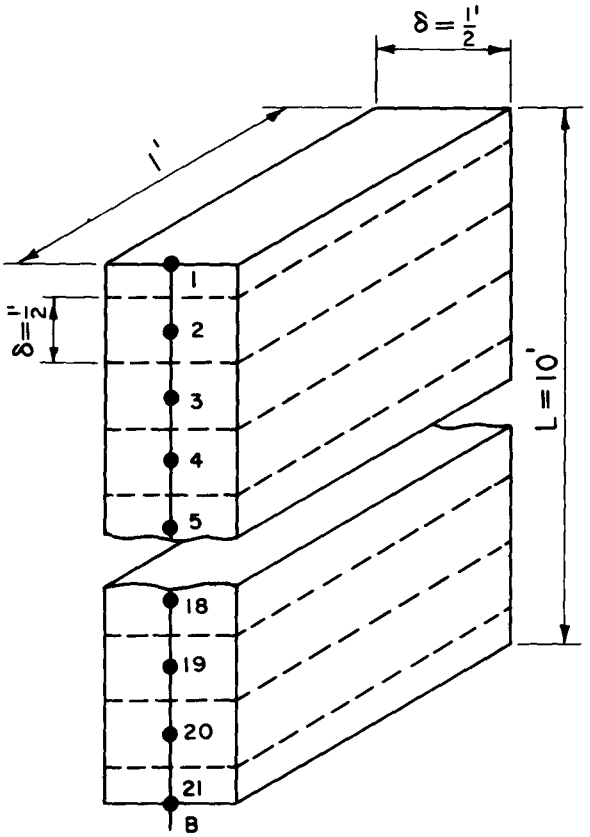

Figure 17. Typical water element.

Equations were written to express the temperature of each internal nodal point at a future time as a function of its present temperature and the present temperature of adjacent nodes. Conservation of energy for each subvolume or node provides that the net energy conducted into a node during a unit of time, $\Delta\theta$, be equal to the change in internal energy:

$$Q_{1\to 2} + Q_{3\to 2} = Q_{STORED_2}$$

$$k(\delta \times 1)\,\frac{(t_1 - t_2)}{\delta}\,\Delta\theta$$

$$+\,k(\delta \times 1)\,\frac{(t_3 - t_2)}{\delta}\,\Delta\theta$$

$$= C_p\rho V(t_2' - t_2), \qquad \text{(V-5)}$$

where t_2' is the future temperature at the end of a finite time interval $\Delta\theta$, and V is the volume of water containing the node in question. Solving the equation for t_2' one obtains:

$$t_1 - 2t_2 + t_3 = \frac{C_p\rho V}{k\Delta\theta}\,(t_2' - t_2). \qquad \text{(V-6)}$$

Evaluation of the equation for the surface node is more complex because of the various energy terms which influence energy exchange at the upper surface. (See description of Anderson's work on energy budget.) A thorough description of the energy terms at the boundary has been presented by Hollen [38]. A brief description of these terms follows:

1. Incident Solar Energy.—The solar energy reaching a surface at the outer fringes of the earth's atmosphere is about 440 Btu/hr-ft^2. However, less solar energy reaches the earth because part of it is absorbed and scattered as it passes through the air, water vapor, and dust that surround the earth.

In a report on radiant properties of monolayer covered water surfaces, portions of which have been incorporated into this report, Wiebelt and Beard [39] presented tabulations of incident solar energy as a function of the above variables. The present analysis used these values, which are reproduced in Table VII, and assumed that the condition under which the water element exists is described by:

Pressure	=	760 mm of Hg
Water vapor	=	40 mm precipitable
Dust	=	300 particles/cc.

Figure 18 shows a graph of the solar radiation incident on the earth as it varies with the sun zenith angle β.

2. Solar Energy Reflected.—The amount of solar energy reflected by the water is equal to the incident solar energy times the water reflectance. One notes that each of these depends on the solar zenith angle, β, or the time of day.

Anderson [33], reporting in the Lake Hefner study, gave the following empirical equation describing his reflectance data:

$$R_t = a\phi^b \qquad \text{(V-7)}$$

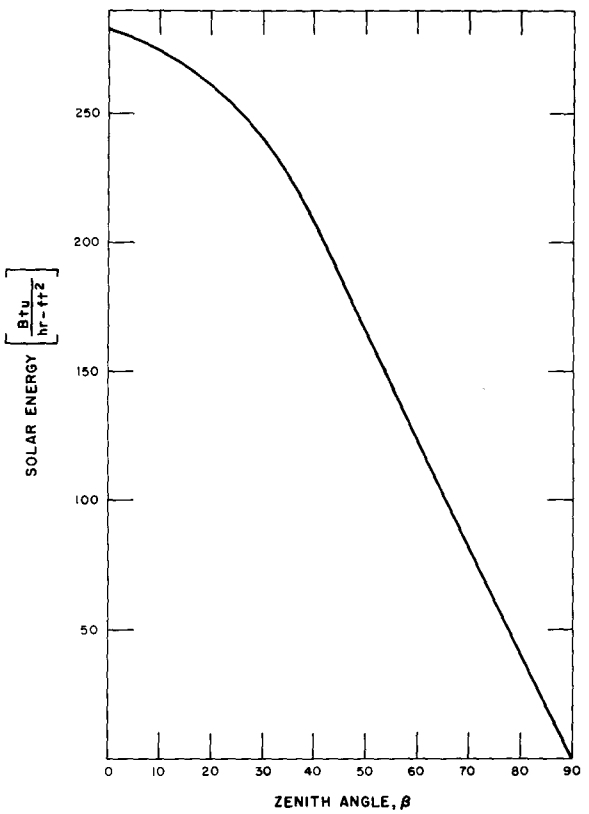

Figure 18. Incident solar radiation as a function of sun zenith angle.

where

R_t = reflectance

a = 1.18

ϕ = angle the sun makes with the horizon ($90^o - \beta$)

b = −0.77.

This equation is used as an approximation for reflectance of solar energy from plain water surfaces.

Upon the application of a reflecting monolayer, the above equation obviously changes. Data for the reflectance of various hypothetical monolayers [36] can be fitted to the general form. Typical examples are illustrated in Table XII.

3. Long Wave Energy Exchange.—It can be shown that the long wave energy exchange can be approximated by assuming the sky to be a black body at the ambient temperature, T_a, and the water to be a gray emitter at the surface temperature, T_S. This gives:

$$Q_b = \epsilon\sigma(T_S^4 - \epsilon_a T_a^4) \qquad \text{(V-8)}$$

where σ is the Stefan Boltzmann constant, ϵ is the emissivity of water, calculated by Hollen to be 0.922, and ϵ_a is approximately 0.78. The ambient temperature is considered to vary as a known sine wave over a 24-hour period.

4. Convection Heat Transfer.—Convection heat transfer is described by the equation:

$$Q_h = h(T_S - T_a), \qquad \text{(V-9)}$$

where h is the convective coefficient, and T_a is the ambient temperature.

A search of the literature found no established relationship for estimating the convective coefficient, h. However, it was assumed that Reynold's analogy for turbulent flow over a flat plate could be used to relate h to shear stress and air properties:

$$h = \frac{g_c \tau}{U_a}\left[C_p\left(\frac{k_a}{\mu}\right)^2\right]^{1/3} \qquad \text{(V-10)}$$

where

τ = surface shear stress

U_a = air velocity

C_p = specific heat at constant pressure of air

k_a = thermal conductance of air

μ = absolute viscosity of air.

Keulegan [40], Fitzgerald [41], and Hutchinson [42] have presented studies on the variation of surface shear stress with wind velocity, and an average of their results was used [38]:

For rough water:

$$\tau = \frac{1}{g_c}\ 28.2 \times 10^{-4}\,\rho_A U^2,$$

and for monolayer-covered, smooth water:

$$\tau = \frac{1}{g_c}\ 19.75 \times 10^{-4}\,\rho_A U^2.$$

Table XII

WATER SURFACE REFLECTANCE

Properties	Equation	Normal reflectance ratio
Monolayer with same reflectance as water	$R_t = 1.18\phi^{-0.77}$	1.00
Monolayer with optical properties: n = 1.30, K = 3.00	$R_t = 1.5\phi^{-0.63}$	2.38
Monolayer with optical properties: n = 1.5, K = 5.0	$R_t = 0.957\phi^{-0.264}$	7.88

Making the above substitutions, one can show that h varies from 1.5 to 6.7 [Btu/hr-ft^2 °F] with wind speeds varying from 7 to 14 mph.

5. Energy of Evaporation.–The Bowen ratio is not a constant when one considers transient heat transfer. Therefore, the energy of evaporation must be calculated separately:

$$Q_e = h_{fg}\,\dot{m}, \qquad \text{(V-11)}$$

where h_{fg} is the latent heat of vaporization and $\dot{m}$ is the evaporation mass flux in [lb_m/hr-ft^2]. The mass flux can be written similarly to the convection heat transfer equation:

$$\dot{m} = h_D(C_w - C_a), \qquad \text{(V-12)}$$

where

h_D = mass-transfer coefficient
C_w = concentration of water vapor disffusing into the air
C_a = concentration of water vapor in the air.

Assuming water vapor and air behave as ideal gases, the concentration terms can be written:

$$C_w - C_a = \frac{M_w}{R_o T}(P_w - P_a), \qquad \text{(V-13)}$$

where

P_w = saturated water vapor pressure
P_a = partial vapor pressure in air.

The mass transfer coefficient is determined by extending Reynold's analogy by the heat-mass analogy. This gives:

$$h_D = \frac{h}{\rho_A C_p (a/D)^{2/3}} \qquad \text{(V-14)}$$

where

C_p = heat capacity
a = thermal diffusivity of air
D = diffusion coefficient of water vapor into air.

Consequently, if one makes the above substitutions, the energy associated with evaporation is a known function of vapor pressures (which is a simple function of temperature) and the diffusion coefficient. The value of the diffusion coefficient depends on the presence or absence of a monolayer. The diffusion coefficient for water vapor into air is given by Eckert and Drake [43] to be:

$$D = 0.892\frac{P_o}{P}\left[\frac{T_S}{T_o}\right]^{1.81} \qquad \text{(V-15)}$$

where

D = diffusion coefficient, ft^2/hr
P_o = 14.22 lb/in^2
T_c = 460° R
P = atmospheric pressure taken as 14.7 lb/in^2.

Making the above substitutions into the above equation, the expression for diffusion is reduced to:

$$D = 0.863 \left[\frac{t_S + 460}{460} \right]^{1.81} \qquad \text{(V-16)}$$

where t_S is in Fahrenheit degrees.

As a cetyl alcohol monolayer is known to act as a diffusion barrier, by reducing evaporation up to 39 percent, it was assumed that the diffusion coefficient should be reduced by 39 percent when a monolayer was assumed present.

6. Summary.—Each of the above energy relations is a function of the temperature of the water surface, which is considered to be an unknown. However, by making an initial temperature assumption and by performing an iterative numerical methods technique, both the daily temperature history and the amount of evaporation can be computed.

Results

Evaporation and temperature histories were calculated for weather conditions of a typical day in spring-fall. The conditions used were:

Water temperature at Z = 10 ft: $T_B = 65^o$ F
Daily mean air temperature: $T_M = 60^o$ F
Deviation from mean temperature to high and low: $T_{amp} = 12^o$ F
Relative humidity = 50 percent
Wind velocity = 15 ft/sec
Number of daylight hours = 12.

A typical history curve is shown in Figure 19. Although the temperature fluctuations are large, the trends indicated compare well with experimental work at Lake Hefner [33]. Analytical results are presented in Table XIII, showing the effects on water evaporation caused by a chemical monolayer that:

1. Decreases the coefficient of water vapor diffusion into air;

2. Decreases the shear stress on the water surface; and

3. Increases solar energy reflectance.

Using the properties of a cetyl alcohol monolayer, calculated values for evaporation reduction were compared with the experimental results of Crow [1]. During a 66-day test period from July to October 1959, Crow obtained a 25 percent reduction using cetyl alcohol on ponds. He further noted that the

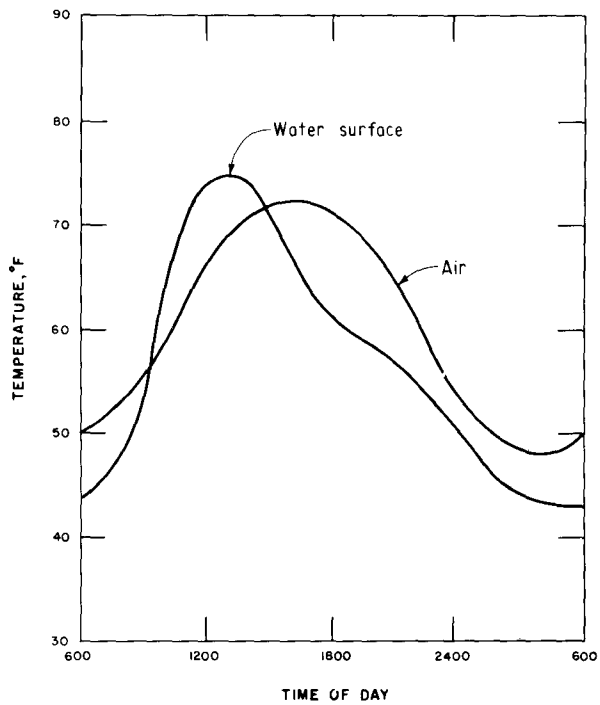

Figure 19. Temperatures for a spring day.

water surface temperature with the monolayer was an average of 5.4° F higher than the surface temperature of a similar uncovered pond.

The analytical results found in Table XIII, using the cetyl alcohol monolayer, show an average evaporation reduction of 21 percent for a similar seasonal period. Also, the water surface temperature increased an average of 5.2° F during the same seasonal period. These analytical results agree closely with Crow and verify the analytical model to be satifactory for calculating evaporation suppression.

Again from Table XIII, the percent evaporation reduction associated with using one highly reflecting monolayer is 36 percent. These results demonstrate that water evaporation is significantly reduced by increasing the solar energy reflectance properties of water surfaces.

CHAPTER VI. EXPERIMENTAL STUDY OF SOLAR REFLECTANCE BY CHEMICAL MONOLAYERS AND FILMS ON WATER SURFACES

Discussion

Many materials that form monomolecular films on water surfaces have been found to be effective

Table XIII

WATER EVAPORATION $\frac{\text{inches}}{\text{day}}$

Surface condition	Normal reflection ratio	Evaporation spring and fall	Percent reduction
No monolayer present	1.00	0.357	
Monolayer representing cetyl alcohol	1.00	0.283	21
Monolayer n = 1.3, K = 3.0	2.35	0.275	23
Monolayer n = 1.5, K = 5.0	7.88	0.227	36

evaporation retardants, partially because they act as diffusion barriers. But the presence of a monolayer or thin film on a water surface also alters the wave action and reflective properties of the water surface, thus altering the radiant energy input to the water body and, consequently, the amount of evaporation taking place. A monolayer forming material that presents an effective diffusion barrier and that also acts as a good reflector should theoretically be most efficient as an evaporation retardant. Attempts to discover or formulate and to test such materials are described below.

The sun's radiation is composed of a spectrum of wavelengths, but the wavelengths of maximum radiation intensity lie in the visible region (0.4 to 0.7 micron). Either a perfect reflector or a reflector that peaks at a wavelength of maximum solar intensity (yellow) should give maximum reflectance.

All of the monolayers which have been shown to be effective evaporation suppressants have been formed from mixtures or impure industrial grade chemicals and all are essentially colorless. No solid yellow monolayer-forming material was found at all and only three yellow liquids capable of forming monolayers were found. Two liquids, linoleic acid and 10-undecanoic acid, in fact, were only very slightly yellow. As shown in Table XIV, using the apparatus of Figures 20 and 21, experimental studies confirmed that these monolayers reflect approximately the same amount of solar energy as does a plain water surface.

The alternative to a natural yellow color is an artificially imposed color of the monolayer material. There are two very important problems with this approach. First, it has been found that impurities, or molecules which do not show the monolayer orientation, actually act as holes in the monolayer and thereby reduce its effectiveness. Very low concentrations of such impurities can completely cancel any evaporation reduction ability the monolayer would have had. Secondly, at high surface pressures, near the equilibrium surface pressure, the monolayer will squeeze out any nonoriented impurities. Thus, by its very nature, a monolayer would discourage the use of dyes. Some dyes with a hydrophilic-hydrophobic structure similar to monolayers were investigated to determine whether they would mix with a monolayer to form a "yellow" surface. A list of these dyes appears in Table XV. The dyes, in powder form, invariably failed to mix with the monolayer material. Solutions of the dyes in benzene, toluene, or acetone were not miscible in the fatty oils. The results of these experiments indicated that dyeing the monolayer was unsuitable.

However, one particular yellow silicone oil, produced by Union Carbide Corporation[2], was found to have desirable reflecting properties. As is shown in Table XIV, when it is spread on water about 1.7 times as much solar energy is reflected as from a plain water surface. This yellow silicone oil was found to exhibit spontaneous spreading properties similar to monolayers and a surface pressure which decreased even as a multilayer was forming so that the interfacial surface tension dropped nearly to zero. More important, it exhibited an ability to reduce evaporation similar to that of monolayers. This silicone oil was the only chemical found which both inhibits evaporation and increases solar reflectance. However, since the actual structure of the oil or mixture of oils was not revealed by the supplier, it is difficult to predict whether this material is capable of forming a monolayer exactly like

[2] The yellow oil is referred to as Union Carbide Experimental Silicone, S-1362-91-2. It was obtained from Mr. T. C. Williams, Chemicals and Plastics Division, Union Carbide Corporation, Tarrytown, N.Y.

Table XIV

REFLECTANCE RATIO MEASUREMENTS

Film substance	Monolayer	Film	Reflectance ratio
1. 10-undecanoic acid (yellow liquid)	X		1.05
2. Linoleic acid (yellow liquid)	X		1.00
3. Hexyl alcohol with Amacel Yellow 5-G (liquid)	X		0.93
4. Hexyl alcohol with Chromefast Yellow (liquid)			
(moderate application)	X		1.01
(excessive)		X	1.22
(large excess)		X	0.83
5. Ethanol with Chromefast Yellow (liquid)	X		1.00
6. Octyl alcohol with Chromefast Yellow (liquid)	X		0.99
7. Union Carbide Yellow (yellow liquid)			
(old batch)	(see discussion)		1.39
(new batch)			1.65
(new batch)			1.69
(after trying to clean monolayer from water surface)			1.52
8. Union Carbide Yellow with Aviation Oil No. 65 (liquid)		X	0.97-1.21
9. L-45 silicone oil (colorless liquid)			
Very thin film		X	1.72 (average)
Thick film (visible)		X	1.45 (average)
10. Aviation Oil No. 65 (liquid)			
(at first)		X	1.81
(later)		X	1.52
(still later)		X	1.30
11. Aviation oil with Dodecyl Alcohol (liquid)		X	0.99
12. Octanoic acid (liquid)	X		0.97
13. Cetyl alcohol (solid)	X		0.94

Table XV

LIST OF DYES INSOLUBLE IN H_2O (WITH PROPERTIES)

Pigment Chrome Yellow; 4-o-Toluene-azo-1-phenyl-3-methyl-5-hydroxy-pyrazol
Soluble in alcohol, nontoxic
Oil Yellow; Dimethylaminoazobenzene
Soluble in alcohol, nontoxic
Oil Yellow AB; Benzene-azo-B-napthylamine
Soluble in alcohol, nontoxic
Oil Yellow OB; o-Toluidine-azo-B-napthylamine
Soluble in alcohol, nontoxic
Quenoline Yellow; 2-quenolylindandione and iso-quenopthalone
Soluble in paraffin and Hydrocarbons
Lithol Fast Yellow GG, 1:1 -Dinitro-5:5-dichloro-diphenil-2:2-di-iminomethane
Pigment Chloride GG; 1:1 -Dinitro -4:4-dichlorodiphenil-2:2-di-iminomethane
Soluble in alcohol
Indanthrene Yellow GK; 1:5-Dibenzoyldiaminoan-thraquinone
Soluble in xylene
Indanthrene Yellow GN; 2:5-Dichloro-1:2-anthra-quinone-thionanthone
Helio Fast Yellow; 1-Salicylamenoanthraquinone
Soluble in pyridine
Hydron Yellow G; N-Ethyl-2:3:2:3 dianthroquinone-carbozole
C. 1. Food Yellow 10, C. 1. No. 11380
Soluble in vegetable and mineral oils
Soluble in stearic acid
Soluble in oleic acid (3.5 gm/100 m1)
Nontoxic
C. 1. Food Yellow 11, C. 1. No. 11390
Soluble in oleic acid (3 gm/100 ml)
Soluble in stearic acid (6.5 gm/100 ml)
Nontoxic
C. 1. Food Yellow 12, C. 1. No. 12740
Soluble in oleic acid
Soluble in stearic acid
Soluble in xylene
Soluble in Benzene
Nontoxic
Amaphlast Yellow PC (Am. Aniline Products) an azo dyestuff
Slightly soluble in Methyl Meth-Acrylate monomer (1.5 gm/100 ml)
Slightly soluble in oleic acid
Amaplast Yellow PFC (Am. Aniline Products) an azo dyestuff
Slightly soluble in methyl-meth-acrylate monomer (1.5 gm/100 ml)
Soluble in oleic acid
Amaplast Yellow EJ (Am Aniline Products) a ceroxone
Soluble in methyl-meth-acrylate monomer (1 gm/100 ml)
Soluble in styrene monomer (2 gm/100 ml)
Slightly soluble in oleic acid

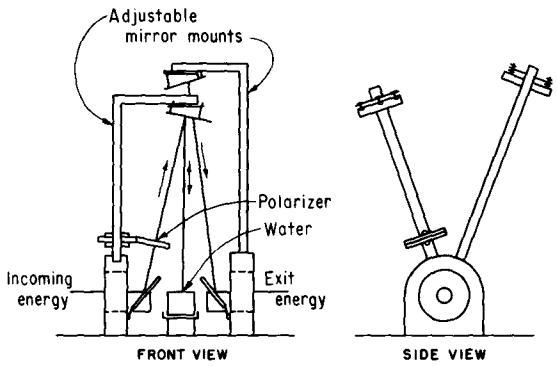

Figure 20. Gonio-reflectometer.

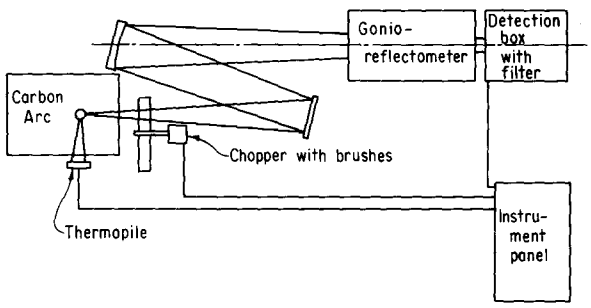

Figure 21. Experimental apparatus.

those previously used for evaporation reduction. Also, since little is known of the molecular properties of the experimental silicone oil, it is not possible to determine whether it fits the equation developed previously for the prediction of diffusion reduction. If it did fit the correlation, that would be strong evidence of orientation at the interface, and, hence, formation of a monolayer.

Once the yellow silicone oil has been used on a piece of equipment, it is quite difficult to clean off. This, although an experimental inconvenience, does indicate a favorable property when applied to a water system. Unlike cetyl alcohol, which is easily cleaned off a water surface by wind, it is projected that the silicone oil will resist such cleaning. In fact, the data of Table XIV indicate the extreme difficulty in cleaning the oil off the water surface. Consequently, the continuous application procedures required at Lake Hefner and other reservoirs might not be required if this silicone oil were used.

Other oils were found to have favorable reflecting properties (L-45 silicone oil[3] and aviation oil No. 65). However, these oils formed as films rather than as monolayers. They appear to have the same undesirable properties (poor oxygen transport, etc.), that are typical of oil films. It is interesting to note that L-45 silicone oil was easy to clean from a water surface, whereas the Union Carbide yellow silicone was virtually impossible to remove from the water surface.

CHAPTER VII
SUMMARY AND CONCLUSIONS

1. An analysis of the diffusion mechanism of water vapor passing through a fully compressed liquid monolayer showed that the diffusion coefficient is directly proportional to surface pressure. Consequently, the simple measurement of surface pressure should indicate the potential for a monolayer to suppress evaporation.

2. Another result of this investigation has been the preparation of detailed radiant energy tabulations for use in energy budgets. These tabulations allow the determination of the radiant energy input to a water storage system with ease and accuracy. Previous evaluations of these quantities required considerable estimation of the basic parameters. By considering the major variables and using high-speed digital computers, most of the variables have been included in the tabulations.

When energy budget techniques are applied to determine the rate of evaporation, it is essential that the radiant input be correctly evaluated. Since this depends on many factors, it was considered that it should be organized to include a minimum number of variables. It would have been desirable to have energy input per month or even per year as the basic quantity, but it was found that so many geographical and climatology variables enter that this was not possible. In the case of the thermal energy input, the tabulations were given on an hourly basis. This was required because many sites are desert-like in climate and have large variations in temperature between night and day. By using hourly units for this radiant input, the daily average or an integrated value may be used. These tables were designed to allow user flexibility. It is suggested that the values from this tabulation be plotted for each hour of a given day and then integrated to obtain the average. This would be required for each of the eight significant dates.

[3] L–45 silicone surfactant oil is widely used in the manufacture of urethane foam. When applied to a water surface, it is very insoluble and forms as a film. L–45 is a polymer of dimethylsiloxone with a molecular weight in the 10,000 to 30,000 range. This oil is marketed by Union Carbide Corporation.

In cases where significant portions of a storage system are not covered by a monolayer, the uncovered portion should have the energy input varied according to the wave pattern on the lake. This investigation did not include a study of wave patterns.

If such information is available, the reflectance values to be used would be modified. A detailed analysis of this reflectance would require the inclusion of wind direction and ratios of wave amplitude to wavelength. Such data would be useful but would require the addition of many more parameters.

3. An analytical solution for water evaporation was presented. Water was assumed to act as a homogeneous solid slab undergoing conduction heat transfer. Boundary conditions were established and a transient numerical solution was used to find the temperature of the water reservoir as it varies with time. Evaporation was calculated for an ideal day in spring-fall. Analytical results of evaporation reduced by chemical monolayers were presented. In computing evaporation with a monolayer present, the diffusion coefficient, water shear stress, and solar radiation reflectance were changed. The results show that water evaporation is decreased by increasing the solar energy reflectance of monolayers and establish the advantage of a highly reflecting monolayer for evaporation suppression.

It is recommended that future studies be made to determine the convection coefficient and wind shear stress of monolayers. This will increase the accuracy of evaporation calculations.

4. For maximum evaporation suppression a monolayer or film should not only act as a diffusion barrier but must also act to limit the amount of solar energy absorbed by the water surface. An analysis of various materials which form stable monolayers or films on a water surface showed only one monolayer that significantly increased the solar energy reflectance (reduced the solar energy absorbed). This was a special Union Carbide Experimental Silicone, S-1362-91-2. In addition to acting as a diffusion barrier and increasing the solar energy reflectance, the film also had good spreading properties and was extremely difficult to remove from a water surface.

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APPENDIX

The energy incident on a surface will be considered to be divided into its polarized components in the plane perpendicular to the plane of incidence (s plane) and the plane parallel to the plane of incidence (p plane). Values for the reflectance of energy in each plane of polarization are designated as R_s and R_p. From an analysis of the electromagnetic theory model of polarized energy, it can be shown that for unpolarized energy the reflectance is

$$R = (R_s + R_p)/2.$$

The analytical expressions for both R_s and R_p have the same form. Therefore, in order to avoid unnecessary equation writing, the subscripts are dropped and the expression for both reflectances is:

$$R = \frac{(g_1^2 + h_1^2)e^{2a} + (g_2^2 + h_2^2)e^{-2a} + A\cos 2\gamma + D\sin 2\gamma}{e^{2a} + e^{-2a}(g_1^2 + h_1^2)(g_2^2 + h_2^2) + C\cos 2\gamma + D\sin 2\gamma} .$$

The following symbols in the reflectance equation are defined to be

$$A = 2(g_1 g_2 + h_1 h_2)$$

$$B = 2(g_1 h_2 - h_1 g_2)$$

$$C = 2(g_1 g_2 - h_1 h_2)$$

$$D = 2(g_1 h_2 + h_1 g_2)$$

$$a = 2\pi bd/\lambda$$

$$\gamma = 2\pi ad/\lambda$$

The following collections of terms used in the previous expressions are defined to be

$$g_{1_s} = \frac{n_o^2 \cos^2 \Phi_o - a^2 - b^2}{(n_o \cos \Phi_o + a)^2 + b^2}$$

$$h_{1_s} = \frac{2bn_o \cos \Phi_o}{(n_o \cos \Phi_o + a)^2 + b^2}$$

where

$$a^2 = \tfrac{1}{2}[n_1^2(1 - k_1^2) - n_o^2 \sin^2 \Phi_o] + \tfrac{1}{2}\sqrt{E}$$

$$b^2 = -\tfrac{1}{2}[n_1^2(1 - k_1^2) - n_o^2 \sin^2 \Phi_o] + \tfrac{1}{2}\sqrt{E}$$

with

$$E = [n_1^2(1 - k_1^2) - n_o^2 \sin^2 \Phi_o]^2 + 4n_1^4 k_1^2$$

Likewise

$$g_{1_p} = (ce + fd)/(e^2 + f^2)$$

$$h_{1_p} = (cf - ed)/e^2 + f^2)$$

where

$$c = n_1^2(1 - k_1^2) \cos \Phi_o - n_o a$$

$$d = 2n_1^2 k_1 \cos \Phi_o - n_o b$$

$$e = n_1^2(1 - k_1^2) \cos \Phi_o + n_o a$$

$$f = 2n_1^2 k_1 \cos \Phi_o + n_o b$$

and

$$g_{2_s} = \frac{(a - a_1)(a + a_1) + (b - b_1)(b + b_1)}{(a_1 + a)^2 + (b + b_1)^2}$$

$$h_{2_s} = \frac{2(ab_1 - a_1 b)}{(a_1 + a)^2 + (b + b_1)^2}$$

where

$$a_1^2 = \tfrac{1}{2}[n_2^2(1 - k_2^2) - n_o^2 \sin^2 \Phi_o] + \tfrac{1}{2}\sqrt{F}$$

$$b_1^2 = -\tfrac{1}{2}[n_2^2(1 - k_2^2) - n_o^2 \sin^2 \Phi_o] + \tfrac{1}{2}\sqrt{F}$$

where

$$F = [n_2^2(1 - k_2^2) - n_o^2 \sin^2 \Phi_o]^2 + 4n_2^4 k_2^2$$

Further,

$$g_{2_p} = \frac{(sa - tb - a_1)(sa - tb + a_1) - (b_1 - at - sb)(b_1 + at + sb)}{(sa - tb + a_1)^2 + (b_1 + at + sb)^2}$$

$$h_{2_p} = \frac{(sa - tb - a_1)(b_1 + at + sb) + (sa - tb + a_1)(b_1 - at - sb)}{(sa - tb + a_1)^2 + (b_1 + at + sb)^2}$$

where

$$s = \left(\frac{n_2}{n_1}\right)^2 \frac{(1 - k_1^2)(1 - k_2^2) + 4k_1 k_2}{(1 + k_1^2)^2}$$

$$t = -2\left(\frac{n_2}{n_1}\right)^2 \frac{k_1(1 - k_2^2) - k_2(1 - k_1^2)}{(1 + k_1^2)^2} \quad .$$

7-1750 (3-71)
Bureau of Reclamation

CONVERSION FACTORS–BRITISH TO METRIC UNITS OF MEASUREMENT

The following conversion factors adopted by the Bureau of Reclamation are those published by the American Society for Testing and Materials (ASTM Metric Practice Guide, E 380-68) except that additional factors (*) commonly used in the Bureau have been added. Further discussion of definitions of quantities and units is given in the ASTM Metric Practice Guide.

The metric units and conversion factors adopted by the ASTM are based on the "International System of Units" (designated SI for Systeme International d'Unites), fixed by the International Committee for Weights and Measures; this system is also known as the Giorgi or MKSA (meter-kilogram (mass)-second-ampere) system. This system has been adopted by the International Organization for Standardization in ISO Recommendation R-31.

The metric technical unit of force is the kilogram-force; this is the force which, when applied to a body having a mass of 1 kg, gives it an acceleration of 9.80665 m/sec/sec, the standard acceleration of free fall toward the earth's center for sea level at 45 deg latitude. The metric unit of force in SI units is the newton (N), which is defined as that force which, when applied to a body having a mass of 1 kg, gives it an acceleration of 1 m/sec/sec. These units must be distinguished from the (inconstant) local weight of a body having a mass of 1 kg, that is, the weight of a body is that force with which a body is attracted to the earth and is equal to the mass of a body multiplied by the acceleration due to gravity. However, because it is general practice to use "pound" rather than the technically correct term "pound-force," the term "kilogram" (or derived mass unit) has been used in this guide instead of "kilogram-force" in expressing the conversion factors for forces. The newton unit of force will find increasing use, and is essential in SI units.

Where approximate or nominal English units are used to express a value or range of values, the converted metric units in parentheses are also approximate or nominal. Where precise English units are used, the converted metric units are expressed as equally significant values.

Table I

QUANTITIES AND UNITS OF SPACE

Multiply	By	To obtain
	LENGTH	
Mil	25.4 (exactly)	Micron
Inches	25.4 (exactly)	Millimeters
Inches	2.54 (exactly)*	Centimeters
Feet	30.48 (exactly)	Centimeters
Feet	0.3048 (exactly)*	Meters
Feet	0.0003048 (exactly)*	Kilometers
Yards	0.9144 (exactly)	Meters
Miles (statute)	1,609.344 (exactly)*	Meters
Miles	1.609344 (exactly)	Kilometers
	AREA	
Square inches	6.4516 (exactly)	Square centimeters
Square feet	*929.03	Square centimeters
Square feet	0.092903	Square meters
Square yards	0.836127	Square meters
Acres	*0.40469	Hectares
Acres	*4,046.9	Square meters
Acres	*0.0040469	Square kilometers
Square miles	2.58999	Square kilometers
	VOLUME	
Cubic inches	16.3871	Cubic centimeters
Cubic feet	0.0283168	Cubic meters
Cubic yards	0.764555	Cubic meters
	CAPACITY	
Fluid ounces (U.S.)	29.5737	Cubic centimeters
Fluid ounces (U.S.)	29.5729	Milliliters
Liquid pints (U.S.)	0.473179	Cubic decimeters
Liquid pints (U.S.)	0.473166	Liters
Quarts (U.S.)	*946.358	Cubic centimeters
Quarts (U.S.)	*0.946331	Liters
Gallons (U.S.)	*3,785.43	Cubic centimeters
Gallons (U.S.)	3.78543	Cubic decimeters
Gallons (U.S.)	3.78533	Liters
Gallons (U.S.)	*0.00378543	Cubic meters
Gallons (U.K.)	4.54609	Cubic decimeters
Gallons (U.K.)	4.54596	Liters
Cubic feet	28.3160	Liters
Cubic yards	*764.55	Liters
Acre-feet	*1,233.5	Cubic meters
Acre-feet	*1,233,500	Liters

Table II

QUANTITIES AND UNITS OF MECHANICS

Multiply	By	To obtain
MASS		
Grains (1/7,000 lb)	64.79891 (exactly)	Milligrams
Troy ounces (480 grains)	31.1035	Grams
Ounces (avdp)	28.3495	Grams
Pounds (avdp)	0.45359237 (exactly)	Kilograms
Short tons (2,000 lb)	907.185	Kilograms
Short tons (2,000 lb)	0.907185	Metric tons
Long tons (2,240 lb)	1,016.05	Kilograms
FORCE/AREA		
Pounds per square inch	0.070307	Kilograms per square centimeter
Pounds per square inch	0.689476	Newtons per square centimeter
Pounds per square foot	4.88243	Kilograms per square meter
Pounds per square foot	47.8803	Newtons per square meter
MASS/VOLUME (DENSITY)		
Ounces per cubic inch	1.72999	Grams per cubic centimeter
Pounds per cubic foot	16.0185	Kilograms per cubic meter
Pounds per cubic foot	0.0160185	Grams per cubic centimeter
Tons (long) per cubic yard	1.32894	Grams per cubic centimeter
MASS/CAPACITY		
Ounces per gallon (U.S.)	7.4893	Grams per liter
Ounces per gallon (U.K.)	6.2362	Grams per liter
Pounds per gallon (U.S.)	119.829	Grams per liter
Pounds per gallon (U.K.)	99.779	Grams per liter
BENDING MOMENT OR TORQUE		
Inch-pounds	0.011521	Meter-kilograms
Inch-pounds	1.12985×10^6	Centimeter-dynes
Foot-pounds	0.138255	Meter-kilograms
Foot-pounds	1.35582×10^7	Centimeter-dynes
Foot-pounds per inch	5.4431	Centimeter-kilograms per centimeter
Ounce-inches	72.008	Gram-centimeters
VELOCITY		
Feet per second	30.48 (exactly)	Centimeters per second
Feet per second	0.3048 (exactly)*	Meters per second
Feet per year	$*0.965873 \times 10^{-6}$	Centimeters per second
Miles per hour	1.609344 (exactly)	Kilometers per hour
Miles per hour	0.44704 (exactly)	Meters per second
ACCELERATION*		
Feet per second^2	*0.3048	Meters per second^2
FLOW		
Cubic feet per second (second-feet)	*0.028317	Cubic meters per second
Cubic feet per minute	0.4719	Liters per second
Gallons (U.S.) per minute	0.06309	Liters per second
FORCE*		
Pounds	*0.453592	Kilograms
Pounds	*4.4482	Newtons
Pounds	$*4.4482 \times 10^5$	Dynes

Table II—Continued

Multiply	By	To obtain
WORK AND ENERGY*		
British thermal units (Btu)	*0.252	Kilogram calories
British thermal units (Btu)	1,055.06	Joules
Btu per pound	2.326 (exactly)	Joules per gram
Foot-pounds	*1.35582	Joules
POWER		
Horsepower	745.700	Watts
Btu per hour	0.293071	Watts
Foot-pounds per second	1.35582	Watts
HEAT TRANSFER		
Btu in./hr ft^2 degree F (k, thermal conductivity)	1.442	Milliwatts/cm degree C
Btu in./hr ft^2 degree F (k, thermal conductivity)	0.1240	Kg cal/hr m degree C
Btu ft/hr ft^2 degree F	*1.4880	Kg cal m/hr m^2 degree C
Btu/hr ft^2 degree F (C, thermal conductance)	0.568	Milliwatts/cm^2 degree C
Btu/hr ft^2 degree F (C, thermal conductance)	4.882	Kg cal/hr m^2 degree C
Degree F hr ft^2/Btu (R, thermal resistance)	1.761	Degree C cm^2/milliwatt
Btu/lb degree F (c, heat capacity)	4.1868	J/g degree C
Btu/lb degree F	*1.000	Cal/gram degree C
Ft^2/hr (thermal diffusivity)	0.2581	Cm^2/sec
Ft^2/hr (thermal diffusivity)	*0.09290	M^2/hr
WATER VAPOR TRANSMISSION		
Grains/hr ft^2 (water vapor) transmission)	16.7	Grams/24 hr m^2
Perms (permeance)	0.659	Metric perms
Perm-inches (permeability)	1.67	Metric perm-centimeters

Table III

OTHER QUANTITIES AND UNITS

Multiply	By	To obtain
Cubic feet per square foot per day (seepage)	*304.8	Liters per square meter per day
Pound-seconds per square foot (viscosity)	*4.8824	Kilogram second per square meter
Square feet per second (viscosity)	*0.092903	Square meters per second
Fahrenheit degrees (change)*	5/9 exactly	Celsius or Kelvin degrees (change)*
Volts per mil	0.03937	Kilovolts per millimeter
Lumens per square foot (foot-candles)	10.764	Lumens per square meter
Ohm-circular mils per foot	0.001662	Ohm-square millimeters per meter
Millicuries per cubic foot	*35.3147	Millicuries per cubic meter
Milliamps per square foot	*10.7639	Milliamps per square meter
Gallons per square yard	*4.527219	Liters per square meter
Pounds per inch	*0.17858	Kilograms per centimeter

GPO 844-068

ABSTRACT

Monomolecular films, acting as diffusion barriers and simultaneously altering the reflective properties of water surfaces, can reduce evaporation. Analytical and experimental studies were made of the radiant energy input to untreated and monolayer-covered water surfaces. Values of direct solar radiation and energy absorbed by a water surface were computed and tabulated for different zenith distances, atmospheric pressures, and moisture and dust contents of the atmosphere. Values for solar energy input to a smooth water surface were computed and tabulated for latitudes of 30, 35, and 40 deg, at elevations of 1000 and 5000 ft, and precipitable atmospheric moisture values of 10, 20, 30, and 40 mm on 8 typical days throughout the year. Procedures for using these tabulations in the energy budget of water bodies are suggested. To estimate daily evaporation rates from water surfaces, an analytical model was developed to apply transient conditions to an element of a typical water reservoir covered by hypothetical films having different optical properties. Evaporation was reduced by 21% for a cetyl-alcohol monolayer and 36% for a highly reflective monolayer with diffusion properties of cetyl-alcohol. A search was made to find film-forming materials with good diffusion barrier properties that would simultaneously increase solar energy reflectance. Yellow dyes were studied in an attempt to color a monolayer, since yellow reflects at wave lengths where solar energy has its peak intensity. Has 43 references.

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DESCRIPTORS–/ *monomolecular films/ *evaporation control/ reservoirs/ alcohols/ evaporation retardants/ *solar radiation/ reflectivity/ dyes/ adsorption/ diffusion/ water surface/ water conservation/ energy budget/ mass transfer/ surface tension/ waves (water)/ *analytical techniques/ temperature/ evaluation/ climatology/ investigations
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