# USES OF MONOMOLECULAR FILM TO REDUCE EVAPORATION ON THE ELEPHANT BUTTE RESERVOIR

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## INTRODUCTION

The increasing population of our planet, Earth, and the ever increasing standards of living have precipitated in a growing demand for water. In 1950, over 175 billion gallons of water were used daily in the U. S. This figure jumped to 220 billion gallons per day in 1955. This was over 20 percent increase in five years. It is estimated that by 1985, the daily demand for water in the United States will reach 600 billion gallons, which is almost double the demand that exists today.

We receive about 20 percent of our water resources from ground water and 80 percent from surface supplies. Twenty-five years from now, a significant proportion of our water will come from desalinization plants and reclamation of waste water. In conserving our water resources, attempts are in progress to develop methods of suppressing evaporation from reservoirs. The research efforts so far indicate that the conservation of water by evaporation reduction may be economically possible.

The loss of water by evaporation from inland reservoirs is considerable. The water lost to the atmosphere by evaporation in eleven western states, exclusive of Alaska and Hawaii, amounts to 11.5 million acre-feet a year, enough to supply the municipal needs of San Francisco for about 90 years. Evaporation losses are quite significant in New Mexico when considered in connection with the present drought conditions and supply of irrigation water in the Lower Rio Grande Valley. In this valley, the water line divides the rich land from waste land and distinguishes prosperity from economic failure. Every citizen in this region is aware that water is the key to the present and future economy.

At Elephant Butte Reservoir, which is a source of water for the Lower Rio Grande Project, the record from evaporation pan shows an average annual loss by evaporation of 99.561 inches. By using the correction coefficients of pans, the estimated annual evaporation from Elephant Butte Reservoir is approximately 75 inches. The surface area of the reservoir, at the normal level, when 1,250,000 acre-feet of water are in the lake is 27,000 acres. The normal loss of water from Elephant Butte Reservoir by evaporation therefore, is 162,000 acre-feet annually, an amount sufficient enough to irrigate an additional 50,000 acres. In fact, the suppression of evaporation from Elephant Butte Reservoir will be a blessing to

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the Lower Rio Grande Project when viewed in the light of past and present droughts. The results of our study of evaporation suppression could lead to a partial solution of domestic and international water problems in our region.

## MEASUREMENT OF EVAPORATION

The process of evaporation, viewed as a problem in turbulent transfer in the atmosphere, has been marked by little influx of new ideas except through the related problems in heat and momentum transfer. Consequently, the practical approaches to the determination of evaporation still lie along two main paths. The first approach concentrates attention on the mechanism of removal of the fluid vapor by diffusion and is primarily applicable to the determination of evaporation rates. The second approach does not require any knowledge of the details of the evaporation process but relies on estimating the amount of energy used in the change from liquid to vapor phase, and, hence, the rate at which water is being removed. The two approaches are referred to as "mass-transfer" and "energy budget method," respectively. In each of these approaches, some assumptions are required to be made relating to the transfer mechanism for fluid vapor to that of heat or momentum. This is likely to remain the situation until direct measurement of evaporation by method of heat energy flux is more widely explored. So far, such measurements of evaporation have tended to lag behind those of heat and shear stress on an air-fluid surface.

## ENERGY BUDGET METHOD

The energy budget approach to measure evaporation was first applied by Schimdt (1), in 1915, to estimate annual evaporation from the ocean. Richardson (2), in 1931, applied the conservation of energy principle to evaporation of lakes. Extensive investigation of the energy budget method for estimating evaporation was conducted in 1952-53 on Lake Hefner (3). The results of the Lake Hefner studies illustrated that evaporation from reservoirs could be accurately determined by the energy budget method. This method has since been used to determine evaporation from several lakes.

The energy budget method is fundamentally an application of the principle of conservation of energy. The principle may be applied to a reservoir to determine evaporation. Basically, it means that the energy which comes into a reservoir must equal the gain in stored energy plus the amount of energy leaving the reservoir. Incoming energy to a reservoir comes from the sun, atmosphere, rainfall and surface run-off. Outgoing energy goes into radiation, heat conduction, evaporated water and surface outflow. The energy budget equation can be stated as:

$$Q_s - Q_r + Q_a - Q_{ar} + Q_v - Q_{bs} - Q_e - Q_h - Q_w = Q_0 \qquad (1)$$

where:

$Q_s$ = Solar Radiation Incident on Water Surface (cal/cm$^2$ day)
$Q_r$ = Reflected Solar Radiation (cal/cm$^2$ day)
$Q_a$ = Incoming Long Wave Radiation from Atmosphere (cal/cm$^2$ day)
$Q_{ar}$ = Reflected Long Wave Radiation (cal/cm$^2$ day)
$Q_{bs}$ = Long Wave Radiation Emitted by Body of Water (cal/cm$^2$ day)
$Q_e$ = Energy Used in Evaporation (cal/cm$^2$ day)
$Q_h$ = Energy Conducted from Body of Water as Sensible Heat (cal/cm$^2$ day)
$Q_v$ = Net Energy Advected into Body of Water (cal/cm$^2$ day)
$Q_w$ = Energy Advected by Evaporated Water (cal/cm$^2$ day)
$Q_o$ = Increase in Energy Stored in the Body of Water (cal/cm$^2$ day)

Heating due to chemical changes, biological processes are neglected as is the component which pertains to energy transfer into and out of the shores and bottom of the reservoir. These components are small for large reservoirs when compared with other terms in the heat energy equation.

To determine energy used for evaporation ($Q_e$), one needs only to rearrange equation (1) and substitute the following functional relations:

$$\beta = \frac{Q_h}{Q_e} \tag{2}$$

where $\beta$ is Bowen Ratio (4) defined as the ratio of sensible heat to energy used in evaporation.

$$Q_w = \frac{C_p Q_e (T_e - T_b)}{L} \tag{3}$$

where:
$C_p$ = Specific heat of water (cal/gm$^o$C)
$L$ = Latent heat of vaporization (cal/gm)
$T_e$ = Temperature of Evaporated Water ($0_c$)
$T_b$ = Temperature of arbitrary base ($0_c$). Usually taken as $0^o$C$^o$

The resulting relation for evaporation energy is:

$$Q_e = \frac{Q_s - Q_r + Q_a - Q_{ar} - Q_{bs} - Q_o + Q_v}{1 + \beta + \frac{C_p(T_e - T_b)}{L}} \tag{4}$$

When all quantities on the right hand side of equation (4) are measured, evaporation can be determined for any length of a time period. The energy budget used to determine the evaporation from reservoirs is not considered accurate for periods shorter than ten days because of the accuracy of measurement of some of the items in equation (4). This limitation was verified in the Lake Hefner Investigations (3).

## INSTRUMENTATION FOR ENERGY BUDGET STUDIES AT ELEPHANT BUTTE RESERVOIR

Various instruments are needed to determine the quantities in the heat-budget approach to determine evaporation. An energy budget station is maintained on the west side of the Elephant Butte Reservoir at Long Point. The station consists of radiation instruments, thermocouple psychrometer, rain gages, wind vane, wind anemometer, Cummings Radiation Integrator and a house trailer to hold the potetiometric and portable recorders as well as to serve as a field workshop and storage facility. The following variables are observed on the three recorders housed in the air-conditioned trailer:

1. Epply pyrheliometer
2. Flat plate radiometer
3. Relative humidity
4. Flat plate temperature
5. Dry bulb temperature
6. Wet bulb temperature
7. Humidity air temperature
8. Surface temperature in CRI
9. Bulk temperature in CRI
10. Wind velocity
11. Wind direction

## SOLAR RADIATION - $Q_s$

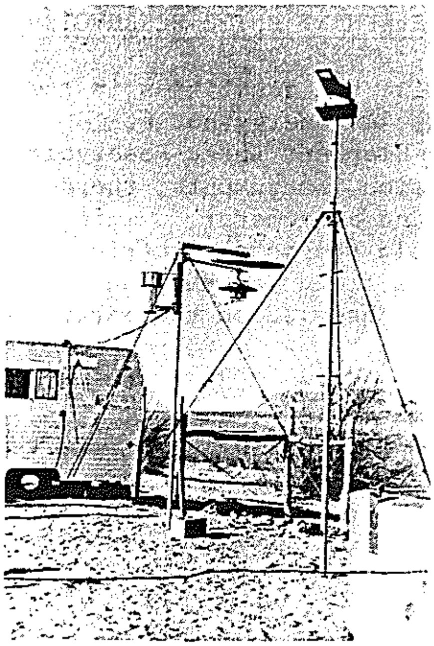
Solar radiation, $Q_s$, is measured with an Epply Pyrheliometer located at the energy budget station. This instrument is placed at the top of a 15-foot pole. The milivolt output from the pyrheliometer is directly recorded in cal/cm$^2$ on the recorder.

## REFLECTED SOLAR RADIATION - $Q_r$

The quantity, $Q_r$, will be indirectly obtained from solar radiation measurement using the method postulated by Koberg (5). Koberg has developed the relationship between reflected solar radiation and incoming solar radiation for clear and cloudy days. A clear day is defined as one in which the ratio of solar radiation to clear-sky radiation exceeds 0.8 and a cloudy day is one in which the ratio is less than 0.8.

## ATMOSPHERIC RADIATION - $Q_a$

The incoming atmospheric radiation, (long wave), $Q_a$ is measured by a flat-plate radiometer. This instrument is also mounted at the top of a 15-foot pole. The output is directly recorded on the recorder in cal/cm$^2$.



Instruments Used at Elephant Butte Reservoir to record data in evaporation control.

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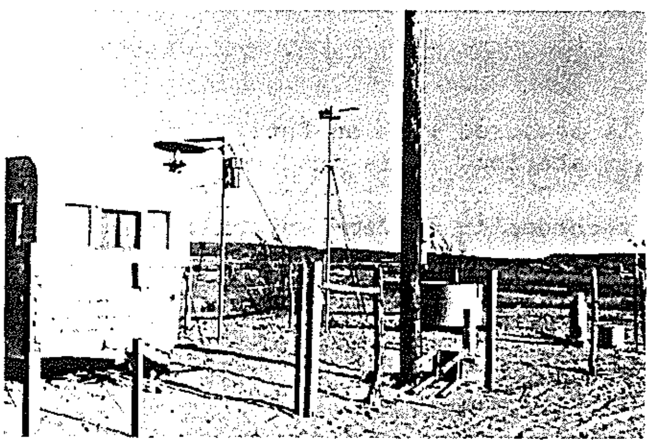

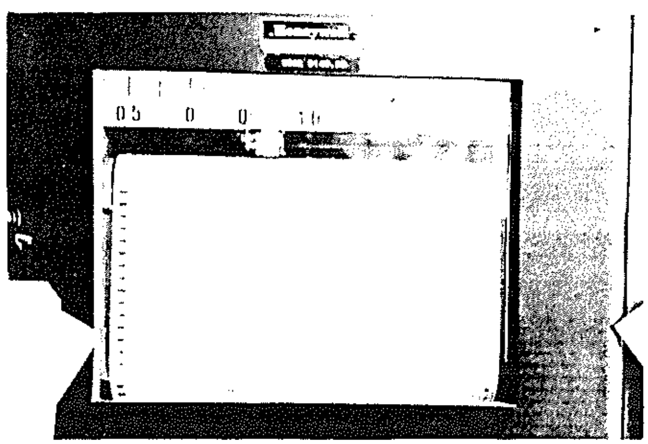

REFLECTED ATMOSPHERIC RADIATION - $Q_{ar}$

The reflectivity of water surface for atmospheric radiation is about 3.0 percent for a water temperature range of $0^oC$ to $30^oC$ as shown by measurements of Gier and Dunkle (6). This quantity will be evaluated after sufficient data are accumulated.

LONG WAVE RADIATION FROM THE RESERVOIR - $Q_{bs}$

Long wave radiation, $Q_{bs}$, from the reservoir will be calculated from Stefan-Boltzman Law for black body radiation. In this computation an emissivity of 0.97 will be used for water suface.

The water surface temperature is recorded at five rafts which are located at different places on the reservoir. Water surface temperature recorders are mounted in boxes on instrument rafts with censer bulb attached to the raft at water surface.

BOWEN RATIO -

The Bowen Ratio is used to determine the relation between the sensible heat, $Q_h$, and energy going into evaporation $Q_e$. This ratio can be expressed as follows:

$$\beta = \lambda \cdot \frac{P}{1000} \cdot \frac{T_o - T_a}{e_o - e_a} \qquad (5)$$

where $\lambda$ = Bowen Ratio Constant = 0.61 ($mb/o_c$)
$P$ = Atmospheric pressure (mb)
$T_o$ = Water surface temperature ($o_c$)
$T_a$ = Temperature of air ($o_c$)
$e_o$ = Saturated vapor pressure of water at water surface temperature (mb)
$e_a$ = Vapor pressure of air (mb)

ADVECTED ENERGY - $Q_v$

The net advected energy, $Q_v$, is the gain in energy from inflow, outflow and rainfall. The volume of inflow is gauged at a station near San Marcial maintained by U.S. Geological Survey. The temperature of the inflow to the reservoir is recorded at Mitchel Point near the entrance of the water into the Lake. The volume of outflow is measured by the U.S. Bureau of Reclamation through their power and irrigation releases at Elephant Butte Dam. An outflow temperature recorder measures the temperature of water released through the dam. The rainfall is measured at the energy budget station with both U. S. Weather Bureau nonrecording and recording type gage. The rainfall temperature will be taken as that of wet bulb temperature at the time of the rain.

## STORED ENERGY - $Q_o$

The energy stored, $Q_o$, in the lake is determined at the beginning and end of each thermal-survey period. At the present, the thermal survey is taken at every two-week interval. The reservoir temperature profile is taken at about 50 sites, out of which 46 are presently accessible, with a Whitney Underwater Thermometer accurate to 0.1°C. The calibration is constantly maintained and checked before and after the thermal survey.

## SUPPRESSION OF EVAPORATION

When a monomolecular film is applied to a lake to suppress evaporation, determination of evaporation, and, more important, the estimate of decrease of evaporation as a consequence of the film becomes complex. A method has been developed by Harbeck and Koberg (7) to determine evaporation reduction which makes use of the heat-budget and mass transfer techniques.

Harbeck and Koberg postulated that when evaporation is reduced, there is an increase in lake surface temperature and the energy which is not utilized in evaporation is returned to the atmosphere by back radiation and conduction. Harbeck and Koberg method also assumes that the film has no effect on net solar radiation, atmospheric radiation, the net advected energy and long time energy storage. Harbeck and Koberg also illustrated that any effect of the film on reflected long wave radiation, $Q_{ar}$, will be largely counterbalanced by a compensating influence on long wave radiation, $Q_{bs}$, emitted by the body of water. The assumption that the film has little influence on the energy storage below the surface may be subject to some doubts, but, at present, it is difficult to determine the magnitude and influence of the additional storage of energy as the result of the film. Harbeck and Koberg assumes it to be negligible. Assuming that the quantities which are appreciably influenced by the film are $Q_e$, $Q_{bs}$, and $Q_h$, it follows that the net sum of the effects with and without the film must be zero, or

$$(Q'_{bs} - Q_{bs}) + (Q'_e - Q_e) + (Q'_h - Q_h) = 0 \qquad (6)$$

in which the symbols with primes refer to the reservoir with a film and the symbols without the primes to the same reservoir without a film.

During the pretreatment period, heat energy utilized in evaporation and conduction are related to their respective mass-and heat-transfer equation as stated below.

$$Q_e = NU\ (e_o - e_a) \qquad (7)$$
$$Q_h = KU\ (T_o - T_a) \qquad (8)$$

Where U = wind speed in MPH
N = constant in cal/cm$^2$ day mph$^o$C
K = constant in cal/cm$^2$ day mph$^o$C

The constants K and N are determined during pretreatment period. Substituting equation (7) and (8) along with equation for back radiation $Q_{bs} = 0.970\ (T_o + 273)^4$ in equation (6), the following equation is obtained:

$$0.970\ [\ (T'_o + 273)^4 - (T_o + 273)^4\ ] + [\ \gamma_e\ \text{EL-NU}\ (e_o - e_a)\ ] + KU\ (T'_o - T_o) = 0 \qquad (9)$$

The above equation is a function of $T_o$ only since $e_o$ is a single valued function of $T_o$. Equation (9) can be solved for $T_o$ and the corresponding values for $e_o$ can be substituted in equation (7) to give the evaporation that would have taken place had the film not been present. The evaporation suppression now can be determined by considering the actual evaporation as computed by equation (1) and the estimated evaporation had no film been present.

In reality, the mass-and heat-transfer coefficients viz. N & K in equation (7) and (8) for no film period are not the same as those for film period as was pointed out by Mansfield (8). Also, the wind profile near the water surface would not be the same for periods with and without film, since the presence of film reduces the development of waves. These influences, however, are considered to be very small on transport constants N and K.

## CHARACTERISTICS OF THE FILM

Following are the most desirable characteristics of film-forming chemicals which are used for suppression of evaporation.

a. The film should have good healing properties
b. The chemical must be inexpensive
c. The chemical should not be consumed too rapidly by bacteria
d. It should be easily applicable
e. It must effectively retard evaporation
f. The material should be insoluble, nontoxic and tasteless.

At Elephant Butte, it is proposed to use Hexadecanol ($CH_3(CH_2)_{15}OH$) also known as cetyl alcohol for evaporation suppression.

## APPLICATION OF THE CHEMICAL

Many different methods of application of the chemical have been tried and proven successful. Hexadecanol is a white, waxy solid at ordinary temperatures. It can be grinded to a fine powder or is obtainable in flake form. The chemical can also be pelletized. The melting point of Hexadecanol is 130°F. It also can be dissolved in solvents like kerosene and petroleum ether. It can be applied to the water surface from wire screen flots, by hand as powder or flakes, as a mechanical suspension sprayed onto water surface under pressure, as solution dissolved in solvent, application as emulsion, and spread onto water in molten condition. At Elephant Butte, it is proposed to apply the chemical by the method developed by Israelsen and Hansen (9) of Utah State University. This method uses an aircraft which dispenses evaporation retardants in liquid or powder form. The parts of the reservoir not accessible by the aircraft will be sprayed by a Robertson-Grinder-Duster mounted on a boat.

FILM DETECTION AND COVERAGE

The detection of the film and the determination of area covered by the film is one of the formidable tasks of evaporation suppression investigation. At Elephant Butte, it is proposed to make hourly determination during daylight hours of the area covered by film. These determinations include film mapping from land vantage points using a plane table, photographs from various vantage points, film pressure measurements using indicator oils and infrared scanner.

COST OF EVAPORATION SUPPRESSION

Various investigators have quoted the cost of conservation of water from suppression of evaporation by the use of monomolecular films. Costs as low as $6.00/acre-foot have been reported; but these seem to be unrealistic. The table below gives the representative costs reported by the Bureau of Reclamation (10). It is anticipated that the saving of water by the application of monomolecular films on reservoirs may range from $20 to $35 per acre-foot once the technique and methodology is perfected. However, it should be realized that the above figure applies to those selected reservoirs which have proper size, shape, moderate winds and high evaporation.

SUMMARY

It can be concluded that reduction in evaporation by means of monomolecular films may become a popular method of saving water in arid and semi-arid regions. A comparison with costs of alternate sources of water reported by Dr. Franzini (11) of Stanford University is shown in the table below. This table shows that the monomolecular film method is competitive. It should be also noted that reduction in evaporation will not result in large quantities of water.

With respect to Elephant Butte Evaporation reduction investigation no general conclusion can be drawn since the project is in progress. It is hoped that significant savings in water and lower

COST OF EVAPORATION SUPPRESSION

| Lake | Test Period | Evaporation Suppression | Cost/Acre-Ft. of Water Saved |
|---|---|---|---|
| Lake Hefner Oklahoma City Oklahoma | July 7- Oct. 2, 1958 | 9 ± 5% | $61 |
| Sahuaro Lake Near Phoenix Arizona | Oct. 1-Nov. 17 1960, Total Test Period. | 14 ± 5% | $69 |
| | Oct. 19- Nov. 17, 1960 Continuous Treatment | 22 ± 5% | $58 |
| Lake Cachuma Near Saint Barbara, Calif. | July 31-Sept. 24, 1961 Total Test Period | 8 ± 5% | $68 |
| | Aug. 14-28, 1961 2nd Thermal Survey | 22 ± 5% | $28 |
| Pactola Reservoir Near Rapid City South Dakota | July 5-Sept. 1, 1962 | Unknown Until Completion of Final Report | Unknown Until Completion of Final Report |
| Elephant Butte Reservoir Elephant Butte New Mexico | Summer of 1965 or 1966 | ? | ? |

COST OF RAW WATER

| | Dollars Per Acre-Foot |
|---|---|
| Local Runoff | $3.00 - 10.00 |
| Ground Water | $3.00 - 10.00 |
| Imported Water | Variable |
| Reclaimed Waste Water | $25.00- 40.00 |
| Sea Water Conversion | |
| Distillation | $250 - 600 |
| Solar Stills | $350 |
| Freezing | $700 |
| Ion Exchange | $8,000* |
| Electrolytic Action | $500* |
| Ion-Permeable Membranes | $3,000* |
| Evaporation Suppression | $20.00 - 35.00 |

* Considerably lower for brackish water

cost of evaporation suppression will be achieved. It is also hoped that the techniques of evaporation determinations and its suppression will be improved. It is also realized that extensive amounts of research and development technique need to be performed before the capabilities of water conservation through evaporation suppression are formulated.


## ACKNOWLEDGEMENT

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## REFERENCES


1. Schmidt, W. "Strahlung Und Verdustrung in Freien Wasserflachen: oin Beitrag Zum Warmehaushalt des Weltmeers Und Zum Wassemhaushalt der Erde" Annalen der Hydrographic Und Maritimen Meteorologie 43:111-124 and 169-178 (1915).

2. Richardson, B. "Evaporation as a Function of Insolation," Trans. ASCE 95:996-1011 (1931).

3. U.S.G.S. Professional Paper 269 "Water Loss Investigation: Lake Hefner Studies," Technical Report:, U. S. Government Printing Office, 1954.

4. Bowen, I. S., "The Ratio of Heat Losses by Conduction and by Evaporation from any Water Surface," Physical Review, Vol. 27, 1926.

5. Koberg, G. E., "Energy-Budget Studies" Water Loss Investigations: Lake Mead Studies, U.S.G.S. Professional Paper 298. .

6. Gier, J. T. and Dunkle, R. V. "Radiation from the Body of Water" in Water Loss Investigation Report of Lake Hefner, Page 96, U.S.G.S. Professional Paper 269, U. S. Government Printing Office (1954).

7. Harbeck, G. E. and Koberg, G. E. "A Method of Evaluating the Effect of a Monomolecular Film in Suppressing Reservoir Evaporation: J. Geophys. Res., 64:89-33 (1959).

8. Mansfield, W. W., "Aspects of Evaporation Control" in LaMer, V.K. (ed), Retardation of Evaporation by Monolayer; Transport Processes, Academic Press N. Y., pp. 133-136 (1962).

9. Israelsen, C. E. and Hansen, V. E. "Evaporation Reduction Investigations of Large Reservoirs," Paper presented at ASCE Water Resources Conference in Milwaukee, Wisconsin, May 1963.

10. Garstka, W. U. "The Bureau of Reclamation's Investigations Relating to Reservoir Evaporation Loss Reduction," Paper presented at Water Evaporation Symposium Sponsored by UNESCO and NCL at Poona, India, December 1962.

11. Franzini, J. B. "Evaporation Suppression Research" in two parts, Journal of Water and Sewage Works, May 1961-June 1963.