Plate 3, "Conjunctive Operation of Surface and Ground-water Reservoir of the San Joaquin Valley Eastside" depicts the monthly operation for the water year 1927 through 1941 for an area from the Mokelumne river south to and including the Kern river. The area was designed to require about 11.5 million acre feet annually which is ninety percent of the mean annual impaired foothill runoff of these streams. As can be seen in Plate 3, conjunctive operation obtained this high degree of conservation with only 6.5 million acre-feet of foothill surface because of the 13.8 million acre feet of ground-water storage capacity used. Upstream storage affords some regulation.

It appears quite certain that conjunctive operation of all basin storage capacity is not only the means of maximizing river basin benefits but for regions similar to California's Central Valley is the only way ultimate water requirements can be economically provided.

RESERVOIR EVAPORATION CONTROL

By

Raymond E. Kerr, Jr.1/

It is particularly appropriate to discuss the subject of evaporation from reservoirs at a meeting involving the Colorado River hydrologists, since the stimulation for some of the most useful work on evaporation that has been published stemmed from the evaporation problem in Lake Mead. The interesting and effective work on evaporation control now under way at the Bureau of Reclamation Engineering Laboratories in Denver was fairly directly initiated by situation in Lake Mead. I shall return to a discussion of the role played by these investigations in a later part of this paper.

My purpose at this time is to give a general background and review of the current state of the science of evaporation control and the hope that we may hold out for effective application to large reservoirs. I make no pretense at being a qualified chemist and much of the future work to be done lies strictly in the domain of chemical engineering. However, we do believe that evaporation is a subject that lies in the proper domain of the meteorologists and that there is a serious contribution that we can make to the full attainment of the efficient application and maintenance of an evaporation reducing film.

The civil engineer can provide many methods of known and unquestionable efficiency in the reduction of evaporation losses simply by reducing the ratio of the exposed water surface to the total volume of water contained. Where evaporation rates are known it is a simple matter to calculate the cost-benefit ratio and to determine the economical alterations to the engineering design of the reservoir and its collection and distribution systems in view of the present and predicted cost of water. Reduction of the surface-to-volume ratio may be accomplished by deepening the reservoirs, filling the banks higher with water, eliminating shallow area, and so forth, and this ratio may be reduced to zero by roofing. Roofing is, of course, expensive and generally uneconomical except in small reservoirs where sanitation is also an important factor, and in practice not as effective as the theory would indicate. Furthermore, the multiple use of many reservoirs complicates the application of these methods, even where the cost-benefit ratio is favorable. For example, a chain of shallow lakes would provide far better conditions for recreation and for wild fowl than would a single steep sided reservoir. Every surviving hydrologist has learned the power of various organizations of sportsmen and wild life conservationists.

The use of polyethylene sheets, perhaps laminated with other materials to increase its efficiency as a vapor barrier has been suggested as a possibility of considerable merit. Although the mass production of this material is lowering the cost to the point where this procedure may become economically feasible, the objection in the case of multiple purpose reservoirs remains, since it would obviously frustrate the ducks should they decide to alight on a polyethylene covered lake.

1/ North American Weather Consultants, Santa Barbara, California.

An alternate method of reduction of evaporation which has long been studied but only recently applied involves the spreading of monomolecular films of certain organic compounds over the water surface. These molecules have a structure which consists of a hydrophobic portion such as a long hydrocarbon chain and a hydrophlic portion such as a hydroxyl, amino or acid group. Not only will such molecules tend to spread out over the surface of the water in a monomolecular layer, but, if the molecules are packed together sufficiently closely, a retardation in the rate of evaporation will be effected.

The two substances that are in the greatest prominence today are representatives of the long chain alcohols specifically cetyl and stearyl alcohol. Fortunately, these substances have other names, hexadecanol and octodecanol, respectively. In view of the fact that we hope to use these materials on public drinking water supplies, etc., it is desirable to avoid the use of the word alcohol. Actually, the substances are not alcohols at all in the popular sense of the word. They are waxy solids and not in the least intoxicating. These substances are widely used in the cosmetics and other industries and are thus readily available and comparatively cheap. The first demonstration that there really was a reduction in the rate of evaporation due to the presence of such a monomolecular film was accomplished by Sir Eric Rideal of Cambridge, England in 1925 (1). Two years later, Dr. Irving Langmuir and his nephew, David Langmuir, (2) reported their findings on a number of substances that were effective in retarding evaporation, and included hexadecanol in this list for the first time. This paper was followed in 1943 (3) by further work by Langmuir and Schaeffer which developed the basic methods for measuring evaporation in laboratory experiments. In two papers published in 1955 (4) and 1956 (5) Professor Victor K. LaMer of Columbia and his collaborators Robert Archer and Henri Rosano tested a number of substances and proved some facts which appear to be at the heart of any successful application of these materials to open water surfaces. Although they found that some of the long chain acids, arachidic acid in particular, were highly efficient in reducing evaporation, and that this effect was independent of surface pressure, once a certain minimum pressure had been achieved, the substances that are commercially available in large quantities and at a low cost were markedly dependent on surface pressure for their efficiency in evaporation reduction.

Thus, although the long chain arachidic acid reached its full efficiency at a surface pressure of 3 to 4 dynes per centimeter and showed no further increase up to 32 dy/cm, octodecanol showed a rapid rise just above 10 dy/cm and thereafter showed a linear increase in "specific resistance" until 42 dy/cm, the highest point recorded, was reached. Hexadecanol reacted in a quite similar fashion, showing a discontinuity at about 20 dy/cm and thereafter the resistance to evaporation rose in a parallel line to the octodecanol line until the maximum pressure of about 44 dy/cm was reached. Of course, that was much more of interest and importance in these two articles, but for our purposes, the essential point is that we may regard it as being proved that evaporation rates are significantly retarded by a monomolecular film of octodecanol or hexadecanol provided we can properly spread and maintain a clean film under adequate pressure.

About the same time that Professor LaMer and his students started their work at Columbia, a group at the Commonwealth Industrial and Scientific Organization in Australia under Mr. M. W. Mansfield and a group at the U. S. Bureau of Reclamation commenced work on the subject. Apparently, the work of the three groups was initiated independently, but quickly led to an interchange of ideas. Although the Bureau of Reclamation work has not yet resulted in literature published in the scientific periodicals, they have published a series of Special Investigations Memoranda (6) and plan to deliver several important papers on the subject this spring (7). These Special Investigations Memoranda have collated available literature and opinion on the subject, and have verified in evaporation pan trials the effectiveness of hexadecanol. Before going further into expanded field trials, they have taken a hard look at, and, in cooperation with the Public Health Service and the Fish and Wild Life Service, have run a number of tests on the effect of these substances on the biological system of a reservoir. Since all Bureau of Reclamation projects are multi-purpose reservoirs where fishing, hunting, and other recreational uses are encouraged, and the water is frequently used for irrigation and human consumption, the importance of these investigations cannot be over-estimated. As a result of laboratory trials and field work, particularly that conducted at Kid's Lake with the cooperation of the Oklahoma City Public Works Department and the Oklahoma State Department of Health, it appears, that no unfavorable effects on the biological system of a reservoir have been established. The very important work of the Australian Group has been summarized in two articles in Nature Magazine by Mr. Mansfield (8, 9), his paper at the First International Conference on Reservoir Evaporation Control held at San Antonio, Texas, April 14, 1956, (10), under the sponsorship of Southwest Research Institute, and finally a C.S.I.R.O. leaflet (11) recommending a process for use on areas of water up to two acres. Mr. Mansfield has dealt with a number of detailed problems, showing the decrease of resistance to evaporation with time, lowering of resistance as a function of air temperature; and the effect of wind speed and solar radiation on the resistance. He has confirmed the dependence of resistance to evaporation on surface pressure for hexadecanol and octodecanol. Results of field trials have been variable but generally encouraging and again there seems to be no doubt that evaporation can be seriously reduced if the surface film can be maintained under adequate pressure. Unpublished reports of field trials in Australia last summer indicate that reductions in evaporation of 30% to 40% were achieved. I do not have the information on the size of the lengths or the length of time that the film was maintained.

The problem of dispersing and maintaining a monomolecular film of 30 to 40 dy/cm surface pressure has thus been recognized and generally agreed on as the central problem in extending the use of those substances to large reservoirs. A film one molecule thick obviously has a quite low tensile strength, and when we have all seen, at least in pictures, ice layers 3 feet or more in thickness crumpled by the shearing stress of the wind over moderately long distances, we can get some ideas of the problem there. On large lakes we can hope that the surface circulation of the water plus the ability of the film to reconstitute plus effective resupply mechanisms will overcome this difficulty. Floating barriers may prove useful in windy locations. Wave action causes further complication due to the stretching and shrinking of the surface, and again, the ability of the film to reconstitute after such action is a matter that is under study. It is an easy matter to provide a clean surface in a Langmuir trough, but impossible to provide or maintain a clean surface in an open lake, and the effect of such contamination is not yet agreed on by the authorities in this field.

One effect of retarding evaporation is to raise the temperature of the water near the surface, which, of course, increases the evaporation rate and also reduces the efficiency of the film. This effect is termed compensation by Mansfield (10) and has been shown to be of importance in reducing the efficiency of the film. Direct action of the sunlight in reducing the long chain molecules to short chain molecules that are ineffective in retarding evaporation has been suspected. Biological oxidation of hexadecanol film has been reported by Ludzack and Ettinger (12) and is also being studied at Southwest Research Institute in San Antonio, Texas. Attempts at control of this phenomena with various copper compounds are under study with some initial success reported by Beadle and Cruse (13). Apparently, this has not been recognized as a serious problem in the Australian work, nor does it appear to have been important in the Bureau of Reclamation Tests on Kid's Lake.

Another problem that is pertinent to the discussion is the very important one of evaluation. Fortunately, we are in fairly good shapehere, largely due to the very fine work done on evaporation at Lake Heffner. This cooperative investigation was carried out by the Bureau of Reclamation, U. S. Navy Electronics Laboratory, the U. S. Navy Department Bureau of Ships, the U. S. Geological Survey and the Oklahoma City Water Department. The Weather Bureau ran some collateral tests on pan coefficients. The report of this work published by the U. S. Geological Survey (14) stands as a most important work on evaporation. This work, plus the availability of Lake Heffner for further tests and field trials and the continuing interest of the Oklahoma City Water Department, has greatly facilitated the prospects of decisive evaluation. The actual water budget control was close enough so that theoretical and empirical formulae could be tested and in future work both the actual and the hypothetical evaporation can be determined with sufficient accuracy to establish the effectiveness of the films.

On the economic plane, we find that material costs may become an important part of the picture. In laboratory trials reduction in evaporation of 99.99% has been achieved. Pan trials have shown reductions of 65% in evaporation, and field trials suggest that 30 to 45% reduction may be achieved. Theoretically, a pound of material would cover 100 acres, but maintenance of a surface film of sufficient pressure for a season in the open is certain to take several orders of magnitude more material than the single application of a theoretical monomolecular layer indicates. Some estimates of material costs of $1.60 per acre have been made for a season's treatment (13).

A very important factor in many areas where water quality is an acute problem, and a factor that may strikingly effect the cost-benefit ratio is the fact that the water lost by evaporation is pure distilled water. Where water with a high concentration of dissolved salts and minerals is subjected to heavy evaporation losses, and consequent concentration of impurities, the result may be to render the entire supply unfit for certain purposes. Thus, in figuring the benefit of evaporation control we can expect to increase the quality and therefore the value of the entire reservoir supply, as well as the quantitative addition of so many feet of water.

The only significant unfavorable effect that has been reported so far has been that on the May flies. Since they are dependent on surface tension at two times in their life cycle, the effect of lowering the surface tension from 75 to 35 dy/cm may prove very disconcerting to them. This is apt to be more apparent than real, at least until it is established that a surface pressure of 40 dy/cm can be continuously maintained over a large reservoir for a long period of time. At worst, this might lead to deliberate lowering of the film pressure and consequent reduction in efficiency during certain critical times.

The present position of the Bureau of Reclamation seems to be that the need is so great and the potentialities so attractive that large scale tests must be conducted. Questions of dispersion of the material and maintenance of a film of adequate pressure are seen as the key questions that can only be answered by full scale trials. The authoritative word on this and on the effect on the biological system of a reservoir will come in papers to be delivered in May by Mr. Moran and Garstka (7) and by Mr. L. O. Timblin all of the Bureau of Reclamation.

There are many aspects of the evaporation control picture that it has not been possible to discuss in this brief resume, and there is a tremendous amount of work to be done in developing the optimum chemicals, method of application and methods of maintaining the film. Remember that a 99.99% reduction has been achieved in laboratory trials while 30% - 40% appears to be the present design figure in field trials. Our special interest lies in determining the meteorological effects on film life, film pressure and film efficiency and in the evaporation measurements necessary for evaluation of full scale trials. It may appear desirable to exercise control of the material dispensing system to minimize material costs and maximize the evaporation retardation rate in view of the climate and weather of a particular project. Right now we are looking forward to the official results of last Summer's work in Australia and at Kid's Lake and the results of the further trials that are to be run this summer on Lake Heffner. We have high hopes that this work will establish the basis for safe and economical methods of checking the loss by evaporation of water that has already been bought, paid for, and stored.

REFERENCES

(1) Rideal, Sir Eric K. "The influence of thin films on the evaporation of water". J. Phys. Chem. 29; 1585 (1925)

(2) Langmuir, I. & Langmuir, D. B. J. Phys. Chem. 31 1719 (1927)

(3) Langmuir, I. and Schaeffer, V. J., J. Franklin Inst. 235 119 (1943)

(4) Archer, R. J. and LaMer, V. K. "The rate of evaporation of water through fatty acid monolayers" J. Phys. Chem. 59; 200 (1955)

(5) Rosano, Henri L. and LaMer, Victor, K. "The rate of evaporation of water through monolayers of esters, acids and alcohols." J. Phys. Chem. 60 348 (1956)

(6) Bureau of Reclamation, Special Investigation Memoranda. Numbers 55-7; 55-10; 55-15; 56-3; 56-11 and 56-14.

(7) Moran, W. T. and Garstka, W. U. "The reduction of evaporation through the use of monomolecular films". To be delivered at the Third Congress of the International Commission on Irrigation and Drainage, at San Francisco in May, 1957.

(8) Mansfield, W. W. "The effect of surface films on the evaporation of water" Nature Dec. 12, 1953.

(9) Mansfield, W. W. "Influence of Monolayers on the evaporation of water" Nature February 5, 1955.

(10) Mansfield, W. W. "The use of Hexadecanol for Reservoir evaporation Control". P. 15-42 Proceedings of the First International Conference on Reservoir Evaporation Control; Southwest Research Institute, San Antonio, Texas. (1956)

(11) Commonwealth Scientific and Industrial Research Organization. "Saving water in Dams" C.S.I.R.O. Leaflet #15, Melbourne, Australia (1956)

(12) Ludzack, F. J. and Ettinger, M. B. "Biological Oxidation of Cetyl Alcohol" undated manuscript, Robert A. Taft Sanitary Engineering Center.

(13) Beadle, B. W. and Cruse, R. R. "Water Conservation through the control of evaporation" Paper presented at Sanitary Engineering Conference, Lawrence, Kansas, January 8, 1957.

(14) U. S. Geological Survey, Professional Paper, No. 269 Water Loss Investigations Lake Heffner Studies Technical Report U. S. Government Printing Office (1954)