WATER TEMPERATURE AS A QUALITY FACTOR IN THE USE OF STREAMS AND RESERVOIRS

by
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Title: WATER TEMPERATURE AS A QUALITY FACTOR IN THE USE OF STREAMS AND RESERVOIRS

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Fiscal Year	OWRR project	Amount, $
1966-1967	A-003-COLO	5,000
1967-1968	A-006-COLO	6,500
1968-1969	A-006-COLO	6,500
1969-1970	A-006-COLO	6,500
4 year total		$24,500

Publications resulting from this project are as follows (Roman numerals indicate entirely separate publications, and multiple listings under a given roman numeral indicate multiple publication of essentially the same paper):

I.(1) Ward, J. C., "Prediction of Beginning and Duration of Ice Cover," Colorado State University Sanitary Engineering Paper No. 2, 34 pages. This paper was presented at the 152nd National Meeting of the American Chemical Society in New York, New York, on September 13, 1966, and was reprinted (abstract) in Volume 6, No. 2, of the Division of Water and Waste Chemistry, Page 47, Paper No. 10. (Partial support by OWRR).

II.(2) Masters thesis entitled, "Predicting the Quality of Irrigation Return Flows," by Gary Alec Margheim, Sanitary Engineering Program, Department of Civil Engineering, Colorado State University, Fort Collins, Colorado 80521, December, 1967, 68 pages.

III.(3) Discussion by John C. Ward, Proceedings of the Specialty Conference on Current Research into the Effects of Reservoirs on Water Quality, January, 1968, Sanitary Engineering Division, American Society of Civil Engineers, pages 299-302.

IV.(4) Masters thesis entitled, "Equilibrium Surface Water Temperatures," by James LaVern Hatheway, Sanitary Engineering Program, Department of Civil Engineering, Colorado State University, Fort Collins, Colorado 80521, June, 1968, 68 pages. (partial support by OWRR).

V.(5) "Economic Considerations in Thermal Discharge to Streams," with G.O.G. Löf, (senior author), presented (by John C. Ward) at the August 14-16, 1968, National Symposium on Thermal Pollution, held at Vanderbilt University, Nashville, Tennessee. This paper is Chapter 10 in the book entitled, Engineering Aspects of Thermal Pollution, edited by F. L. Parker and P. A. Krenkel, Vanderbilt University Press, 1969, pages 282-312. (partial support by OWRR).

VI.(6) "Characteristics of Aqueous Solutions of Cattle Manure," by John C. Ward and E. M. Jex, presented (by John C. Ward) at the January 13-15, 1969, Cornell University Conference on Agricultural Waste Management (Animal Waste), Syracuse, New York, pages 310-326. (partial support by OWRR).

VII.(7) "Evaluation of the Effect of Impoundment on Water Quality in Cheney Reservoir," By John C. Ward and S. Karaki, Colorado State University Sanitary Engineering Paper Number 4, 80 pages, September, 1969. (partial support by OWRR).

(8) Number (7) above also published as Colorado State University Hydrology Paper Number 38, March, 1970.

(9) Number (7) above was also published by the U.S. Bureau of Reclamation as Research Report No. 25, United States Government Printing Office, Washington: 1971. For sale by the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402, or the Bureau of Reclamation, Attention 900, Building 67, Denver Federal Center, Denver, Colorado 80225. Price $1.

(10) An extended abstract of number (7) above will be printed in the proceedings of the International Symposium on Man-made Lakes (Their problems and Environmental Effects), Knoxville, Tennessee, May 3-7, 1971.

VIII(11) "Economics of Thermal Pollution Control," by George O.G. Löf, and John C. Ward, Presented (by John C. Ward) at the 42nd Annual Conference of the Water Pollution Control Federation, October 5-10, 1969, Dallas, Texas. Published in Industrial Water Engineering as "Economics of Thermal Discharges," January, 1970, pages 11-18. (partial support by OWRR).

IX.(12) "Economics of Thermal Pollution Control," by George O.G. Löf and John C. Ward. Journal Water Pollution Control Federation, December, 1970, pages 2102-2116, (partial support by OWRR).

(13) Number (12) above was also published as Reprint Number 91 of the RFF (Resources for the Future, Inc.) Reprint Series. This series makes available in limited quantities reprints of selected papers written by RFF staff members and originally published in journals or proceedings. Single copies are free on request. Janauary, 1971.

X.(14) "Optimization (Minimum Cost) of Cooling Tower Design and Operation," by John C. Ward and George O.G. Löf. This paper has not been published. However, it will definitely be published. Because it is so closely related to IX.(12) above, extended abstracts of both papers are given in this report.

XI.(15) Masters thesis entitled, "Surface Water Heat Balance Experiments," by Koto Kumar Phull, Sanitary Engineering Program, Department of Civil Engineering, Colorado State University, Fort Collins, Colorado 80521, November, 1971, 112 pages. (partial support by OWRR).

John C. Ward was the major professor for all 3 of the Masters theses listed above (2, 4, and 15). Unless specifically indicated otherwise, OWRR was the sole sponsor of the aforementioned 15 publications (11 different papers). Following is a brief discussion of each of the aforementioned 11 papers supported in whole or in part by OWRR.

I. PREDICTION OF BEGINNING AND DURATION OF ICE COVER

by

J.C. Ward[1]; A.M. ASCE

SYNOPSIS

Ice cover is related to the capacity of streams to assimilate wastes because it cuts off air contact, and winter conditions may, in certain circumstances, produce worse oxygen deficits than summer conditions, in spite of the slower rates of deoxygenation and the higher oxygen saturation values of cold waters. The annual variation of stream water temperature can be well represented by a sine curve for most streams[2]. However, streams in cold regions may be frozen over for as much as six months per year. In order to represent the annual variation of stream water temperature for these streams, a modification of the sine curve is necessary. The validity of the modified curve for streams that are frozen over for a portion of a year is indicated in that the duration and beginning date of ice cover is reasonably well predicted, and the stream water temperatures for the rest of the year are also predicted with a fair amount of accuracy.

The effects of thermal pollution on the sine curve are reviewed, and the possible effect on ice cover is indicated.

The possible application of the sine curve to lakes and reservoirs is illustrated.

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[1] Associate Professor of Civil Engineering, Department of Civil Engineering, Colorado State University, Fort Collins, Colorado.

[2] Ward, J.C., "Annual Variation of Stream Water Temperature," Journal of the Sanitary Engineering Division, ASCE, Volume 89, No. SA6, Proc. Paper 3710, December, 1963, pages 1-16. Closure, Volume 91, No. SA1, Proc. Paper 4213, February 1965, pages 69-74. Digest, Transactions, ASCE, Volume 130, 1965, pages 258-260.

II. ABSTRACT OF THESIS

PREDICTING THE QUALITY OF IRRIGATION RETURN FLOWS

A study has been undertaken to express in mathematical terms some of the major factors which affect the quality of irrigation return flows, and to fit these factors into an overall computer program which can be used to predict the quality of the return flows.

The development considers a four-phase system. The phases are: (1) a solution phase, (2) an exchange phase, (3) a crystalline salt phase, and (4) a ground water-deep percolation water phase. For purposes of this study the exchange phase and solution phase were limited to Ca^{++}, Mg^{++}, and Na^{+} ions with $CaSO_4$ present in the crystalline salt phase.

By assuming that a distinct interface existed between the ground water and deep percolation water it was possible to calculate the percent of flow which was ground water. Knowing the quality of the ground water and the deep percolation water, it was then possible to predict the effluent quality.

Although the computer technique developed is quite limited, with the proper measured or assumed variables for the system of concern, it may be used to rapidly predict the quality of irrigation return flows.

Gary Alec Margheim
Civil Engineering Department
Colorado State University
Fort Collins, Colorado 80521
December, 1967

III. <u>John C. Ward, Colorado State University</u>: I would like to present probably the simplest equation of the entire meeting, and this is an empirical relationship with three parameters that you can fit by least squares.

$$T_c = a \sin(bx + c) + \overline{T}_c$$

where

T_c = calculated temperature of the stream water, degrees Fahrenheit (°F)
a = amplitude, °F
b = 0.987 degrees per day (or 0.0172 radians per day)
x = number of days since October 1 (x = 1 for October 1), days
c = phase coefficient, degrees
$\overline{T}$ = arithmetic mean or average value of T_c (if all values of T_c are distributed at uniform intervals of time through-out the year), °F.

I think it offers some help perhaps in handling large masses of data in a fashion that is readily amenable to computer programming, etc. For example, in the energy budget calculations on streams, the rate of change of temperature as a function of time of year is a useful parameter and a necessary parameter doing all right, but the temperature was dropping throughout the lake and the bubbling program was discontinued on the basis that they might freeze the reservoir to a considerable thickness and perhaps the entire depth.

IV. ABSTRACT OF THESIS

EQUILIBRIUM SURFACE WATER TEMPERATURES

A study has been conducted to develop a method of predicting the equilibrium surface water temperature of rivers and lakes either under natural conditions or with thermal pollution.

The development includes consideration of heat transfer by : (1) evaporation, (2) convection, (3) radiation, and (4) solar radiation. Using known mean monthly values for all parameters, a mass transfer coefficient was calculated. This mass transfer coefficient was correlated empirically with the mean monthly wind velocity. This mass transfer coefficient was obtained from a study of several rivers and one lake.

James LaVern Hatheway
Civil Engineering Department
Colorado State University
Fort Collins, Colorado 80521
June, 1968

V. ECONOMIC CONSIDERATIONS IN THERMAL DISCHARGE TO STREAMS

The economic consequences of thermal discharge from steam-electric power plants, the largest users of cooling water, insofar as subsequent cooling uses are concerned, are modest increases in operating costs by the downstream users. These increases are not great enough, however, to justify pre-cooling in the downstream users' plants, unless in-plant economies or thermal-discharge regulations require these plants to employ recirculation cooling. Recirculation cooling is invariably used by plants on small streams where flows are inadequate for once-through cooling. In numerous additional situations, the costs of recirculation cooling, typically approaching one cent per thousand gallons of water, are less than the cost of withdrawing and pumping on a once-through basis. In the large majority of locations, however, generally in water-abundant regions, on-site costs of recirculation cooling in power plants are higher than once-through systems. The costs are also higher than the damages which downstream cooling-water users may suffer through use of warmer cooling water than would otherwise be naturally available. These damages do not include, however, those associated with effects on stream ecology, navigation, or other factors.

Justification for temperature standards in streams cannot rest solely on the economies of alternate methods of cooling. Other considerations appear to be of more significance in establishing limits on heat discharge. But these because in the energy budget this term will ordinarily represent, on the average, and this is a rough figure, approximately 1 percent of the incoming solar radiation per foot of effective depth. Although this is set up on an annual basis, perhaps the same treatment could be applied on a daily basis.

Figure 1 is a plot of temperature versus time on an annual basis. This is an entire year's record, so points represent monthly average values. We had, as you would expect, a greater variation of temperature at these more shallow layers, and, eventually, at the greater depths, the variation of temperature is not in any way represented by a sine curve. The dotted lines show the standard deviation at the 375-foot depth. The points on the diagram are from another year, showing some differences, mostly during the colder season, but the curves represented here, for the most part, explain 90 percent of the variance. But as you can see, there is some difference from one year to the next. The point here is that you can use the sine curve to make a rough estimate for these energy budget calculations that you would do on a stream, and apply to this surface water temperature in a reservoir, although of course you are neglecting, in the first approximation, the exchange of energy between the surface layer and underlying layers. I might mention that it looks like in this case that about one over-turning per year is occuring. The temperature in Lake Mead apparently never gets down to the temperature of maximum density of water.

Now I wonder if it might be possible to classify those lakes with a surface temperature that drops below the temperature of the maximum density of water separately from those lakes in which the water temperature does not drop below the temperature of the maximum density of water. Certainly the ones that do have minimum temperatures less than 4°C, if there is not too much inflow and outflow, give us the more or less classical spring and fall overturning, but it does not appear that this is the case in this particular example, Lake Mead.

Figure 2 is simply a plot of these average temperatures about which the sine curve revolves as a function of depth. With respect to conventional plotting--it is turned sideways. There certainly isn't a linear variation with depth. It is interesting that the temperature tends to level off beyond certain depths, say about 280 feet, and is more or less constant to the bottom. The difference between that minimum temperature shown there and the curve is essentially the amplitude of the sine curve.

Figure 3 is an idealized version of the application of a sine curve to a lake where the surface temperature drops below the temperature of maximum density of water, or perhaps even freezes over as illustrated here. This is, of course, highly simplified, and perhaps it would work and perhaps not. I might mention that some of these lakes that are frozen over, and there are some extreme cases such as in the Rocky Mountains, the entire fish life is extinguished annually by the surface cover of ice. And sometime ago, if I have got the facts straight, the Bureau of Reclamation attempted to bubble some air into these lakes so that the fish could survive the winter. The temperature of the lake, I think, at the outset of bubbling was something like 0°C at the surface and 4°C at the bottom. As the bubbling progressed, I guess the fish were now seem to be of sufficient importance to dictate wide use of recirculation cooling in future steam-power installations. Even in these cases, the additional on-site costs incurred by the power plant (and passed along, in turn, to the power users), due to recirculation cooling, are only a small percentage of total cost of electricity generation and distribution.

VI. CHARACTERISTICS OF AQUEOUS SOLUTIONS OF CATTLE MANURE[a]

by

John C. Ward[1] and E. M. Jex[2]

INTRODUCTION

This paper is, in part, a condensation of a Master's Thesis by E.M. Jex, and because of space limitations, it will be necessary in many cases to state results without the corresponding experimental and theoretical verification. Therefore, for additional details, the reader is referred to the aforementioned thesis.

The primary objective of this study was to investigate the aqueous characteristics (biochemical oxygen demand, conductivity, pH, oxidation-reduction potential, coagulation and colloidal properties, dissolved solids, volatile solids, and foaming) of solutions of cattle manure (throughout this paper, the term manure will be used to indicate the combined urine and feces present in samples from cattle feedlots). This information could then be used in the design of facilities for treating runoff from cattle feedlots. It was assumed that treatment of this runoff would probably be by means of lagoons used to capture the runoff, and that these lagoons would be artificially aerated. In this type of aerobic treatment, the biochemical oxygen demand (BOD) is satisfied in much the same way as in a stream.

Studying the effect of temperature on BOD is facilitated using animal manures rather than mixtures of garbage and human wastes because the results are more reproducible. The experiments showed clearly that both

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[a]Presented at the January 13-15, 1969, Cornell University Agricultural Animal Waste Conference, held at the Hotel Syracuse, Syracuse, New York.

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the rate of exertion and the total BOD exerted increase greatly with temperature up to about 38.3°C. Above this temperature the rate of exertion of BOD decreases. The time, t_L, required for the completion of the BOD reaction in a batch reactor is as follows:

Temperature, °C	t_L, days	fraction of total BOD @ 38.3°C
0	68.7	0.28
10	27.2	0.34
20	14.7	0.45
30	10.6	0.67
38.3	9.8	1.00

Subsequent experiments have demonstrated that the results are applicable to domestic wastewaters where better data is lacking.

VII. (7) EVALUATION OF THE EFFECT OF IMPOUNDMENT ON WATER QUALITY IN CHENEY RESERVOIR

ABSTRACT

A study was conducted to determine the effect of impoundment on the quality of water in Cheney Reservoir. Physical, chemical, and biological data were collected outside the framework of this study. This study concerned only the analysis of the data and the conclusions drawn from the analysis.

Cheney Reservoir did not stratify during the period of data collection. This is substantiated by lack of vertical gradients of temperature, turbidity, and conductivity. There is a longitudinal gradient, but this is a natural result of the differences in concentration of the water in the North Fork of the Ninnescah River and in the reservoir. As a consequence of the vertical homogeneity of this relatively shallow reservoir, the multiple level outlet was not particularly useful during the study period.

Increase in the dissolved solids concentration was shown to be directly related to evaporation. Approximately 42 percent of the total inflow is evaporated from Cheney Reservoir. The most prominant cations were calcium, magnesium, and sodium. The analysis of data for calcium indicated that a limit in concentration had been reached and that precipitation in the form of $CaCO_3$ must be taking place. The slight decrease in concentration of calcium with time is related to the pH of the reservoir water. The increase in magnesium and sodium ions from 11 to 18 mg/ℓ and 120 to 230 mg/ℓ, respectively, are shown to be related directly to evaporation.

The most prominant anions were bicarbonate, sulfate, and chloride. It was shown that nearly all the alkalinity in Cheney Reservoir was due to bicarbonate ion which increased from 134 to 230 mg/ℓ (as $CaCO_3$) and was directly related to evaporation as were the sulfates and chlorides. The sulfate ion concentration was still at a safe level of about 89 mg/ℓ where the limit for drinking water is considered to be 250 mg/ℓ, and the chlorides increased from 150 to 250 mg/ℓ. A complete tabulation of the chemical concentration of Cheney Reservoir water is given in Table 6-2 with values of measured and predicted increases.

Suggestions are presented for control of dissolved solids concentration. Clearly, control of evaporation is indicated, but this alone will not be the solution, for the increase in reservoir temperature and resultant increase in biological activity may well present an undesirable condition within the reservoir. Bypassing some of the poorest quality waters of the North Fork of the Ninnescah is suggested in order to reduce the concentration of dissolved solids both in Cheney Reservoir and in the stream below Cheney Reservoir.

The biological activity within this reservoir did not seem to affect the water quality materially. Odor appears to have stabilized at a threshold odor number of about 5, and is characteristically musty, such as that of decomposing straw. The effect of the interaction between the microorganisms and nutrients were characterized in the analysis of the phosphates, nitrates, and silica concentrations in Cheney Reservoir.

The data which were collected and used in the analysis have been adapted to the national water quality data storage and retrieval system (STORET) and filed with the center in Washington, D. C.

(8) Key Words (descriptors): Dissolved Solids, Evaporation Control, Water Temperature, Reservoir Evaporation, Water Chemistry, Water Balance, Bypasses, Heat Budget, Salinity, Reservoir Design

Abstract: A study was conducted to determine the effect of impoundment on the quality of water in Cheney Reservoir. Cheney Reservoir did not stratify during the period of data collection. The increase in the dissolved solids concentration was shown to be directly related to evaporation. On an annual basis, 42 percent of the total inflow was evaporated from Cheney Reservoir. Suggestions are presented for control of dissolved solids concentration. Clearly, evaporation control is indicated, but the increase in reservoir temperature (12 to 19°F) may present an undesirable condition. Bypassing some of the poorest quality waters of the stream serving Cheney Reservoir is suggested in order to reduce the dissolved solids concentration both in the reservoir and in the stream below the reservoir. The biological activity within this reservoir did not seem to affect the the water quality materially. Odor appears to have stabilized at a threshold odor number of about 5. The effect of the interaction between the microorganisms and nutrients were characterized in the analysis of the phosphates, nitrates, and silica concentrations in the reservoir. The dissolved oxygen percent saturation decreased somewhat from 100 percent at the water surface to roughly 82 percent at a depth of 25 feet.

Reference: "Evaluation of the Effect of Impoundment on Water Quality in Cheney Reservoir," by J. C. Ward and S. Karaki, Colorado State University Hydrology Paper No. 38, Fort Collins, Colorado, March, 1970.

VIII ECONOMICS OF THERMAL POLLUTION CONTROL

by

George O. G. Löf and John C. Ward

ABSTRACT

The large cooling water demands of the electric power industry and the rapid annual growth in these demands are resulting in increased attention to the technical and economic factors related to heat discharge from large power plants. Previous studies have shown that although once-through cooling water use is much more widely practiced than recirculation, power generation costs are usually only slightly higher (and occasionally lower) when cooling towers are used. This paper shows how these costs are determined and extends the method to forecast the extent of recirculation cooling over the next two decades. The off-site costs of thermal pollution on downstream cooling water users are also shown.

Recent and rapid changes in the industry and their influence on heat discharge practices and costs are recognized by inclusion of new estimates on nuclear plants with their lower thermal efficiencies, future growth of natural draft cooling towers, shifts toward progressively larger plants, increased severity of site requirements, and the use of higher condenser temperatures. Evaluation of these trends, in light of the economics of recirculation versus once-through cooling, has yielded extimates of gross water requirements and net water consumption (evaporation) by the electric power industry over the next 20 years.

IX. ECONOMICS OF THERMAL POLLUTION CONTROL

by

George O. G. Löf[1] and John C. Ward[2]

(EXTENDED ABSTRACT)

The cost of cooling water recirculation is composed of capital costs, primarily of the cooling tower installation, and operating costs, which are the makeup water, chemicals, and power for fans and pumps. The capital costs of the tower are in turn dependent on the water flow required, the prevailing wet bulb temperature of the air, the water temperature change through the tower (equal to the temperature rise through the power plant condenser), and the temperature of water delivery from the cooling tower to the condenser. On the basis of this information, the capital cost of the cooling tower installation can be estimated from charts and tables. For

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example, (1), the cooling of 50,000 gallons per minute from 90°F to 75°F at a wet bulb temperature of 65°F would require an investment of approximately $640,000. This tower would serve the cooling needs of a small conventional-fuel plant of about 70,000 KW capacity (at 35 percent thermal efficiency). The annual investment expense, C_I, in cents per thousand gallons of water circulated, may then be computed from the equation,

$$C_I = \frac{I(r + 1/t + P)}{5.256\ N} \qquad (1)$$

where

- I = cooling tower investment per unit capacity, dollars/gpm
- r = annual cost of capital (interest rate), decimal per year
- t = cooling tower service life, years
- P = annual property taxation rate, decimal per year
- N = load factor (fraction of year that cooling tower is used), dimensionless decimal.

The denominator of Eq. 1 is equal to 525,600 minutes/year times N times 10^{-3} to convert into one-thousand gallon units times 10^{-2} to convert dollars to cents. The total capital cost of a forced draft cooling tower (I) may be taken as about $8 per gpm times a relative rating factor, K*. Ordinarily, $0.5 \leq K \leq 1.6$. Cooling towers have long service life (t), which is estimated to range from twenty to forty years for large towers. Under typical conditions, the capital cost (C_I) for a forced draft cooling tower may be about 0.3 cent per thousand gallons circulated.

Relations for costs of operation, C_o, in cents per thousand gallons of water circulated, may be summarized in the following equation (1):

$$C_o = 0.001R\left(\frac{C}{C-1}\right)(0.033Y + 17/C + Wa) + (0.14K + 0.005A)\ p \qquad (2)$$

where

- R = cooling range (temperature change of the water passing through the cooling tower), °F
- C = cycles of concentration, dimensionless (i.e., the ratio of makeup

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* Note that this cost figure is based on water circulation rate, not power plant capacity. The two bases are related to each other, their ratio being dependent on power plant efficiency and cooling range. Table 1 shows the values of water circulation rate required per kilowatt of generating capacity. A "typical" capital cost of a forced draft tower per kilowatt of conventional capacity (38 percent efficiency, 15 degree range) would therefore be $8 x .62 x x K = $4.95K. At a design wet bulb temperature of 65°F and with a water cooling requirement of 90°F to 75°F, K is 1.6 (see reference 2). Thus, the capital cost of a conventional cooling tower for such a fossil fuel power plant would be about $8 per KW of capacity.

water to the sum of drift loss plus blow-down)

Y = alkalinity (as $CaCO_3$) of makeup water, mg/l

Wa = cost of makeup water, cents per thousand gallons

K = relative rating factor of the cooling tower (the relative size of the tower compared with one for the same water flow but operating at a set of "standard" conditions), dimensionless

A = height to which the water must be pumped for flow through the cooling tower, feet

p = cost of electric power, cents/KWH.

Assumptions made in the development of Eq. 2 are:

1. Evaporation of 0.001 pound of water will cool one pound of water 1°F.
2. The price of sulfuric acid is 4 cents per pound. If the price is 2 cents per pound, the quantity $0.033Y + 17/C$ is replaced by $0.017Y + 13.3/C$.
3. Fan horsepower = 0.01KL horsepower, where L = total water flow through the cooling tower in gpm. Actual values may range from 0.007KL to 0.013KL horsepower. If the tower is natural draft (no fans), then the term 0.14K is zero.
4. 0.5KWH is consumed in lifting 1,000 gallons of cooling water 100 feet.
5. Fan electric motor efficiency = 90 percent.

It is common practice to operate moderate sized cooling towers with $3 \leq C \leq 4$, but power plant cooling can usually be more economical if less blow-down is employed and $8 \leq C \leq 10$. If one chooses values of some of the parameters in Eq. 2 as follows: C = 9, y = 150 mg/l, then one obtains

$$C_o = 0.00113R\,(6.9 + Wa) + (0.14K + 0.005A)\,p \quad . \qquad (2a)$$

Table 1
Gallons per minute of cooling water circulation required per KW power capacity.

Overall Efficiency %	Cooling Range, R, °F				
	10	15	20	25	30
30	1.37	0.91	0.68	0.55	0.46
35	1.07	0.72	0.53	0.43	0.36
38	0.93	0.62	0.47	0.37	0.31
40	0.85	0.57	0.42	0.34	0.28
42	0.78	0.52	0.39	0.31	0.26

Values of K (for forced draft cooling towers) to be used with Eq. 1, 2, and 2A are given in reference 2. The condenser inlet temperature (°F) is equal to the sum of the wet-bulb temperature and the approach*. The temperature of the

* "Approach" is defined as the number of degrees (F) that the temperature of cooling water at condenser inlet (and cooling tower outlet) exceeds the wet-bulb temperature.

water from the condensers before cooling is the condenser inlet temperature plus R. Therefore the temperature of the hot water is the wet-bulb temperature plus the approach plus R.

Under typical conditions, the operating cost (C_o) may approximate 0.5 cent per thousand gallons. Hence, total costs of recirculation may be about 0.8 cent per thousand gallons. At a water temperature increase through the condensers of 15°F and a current average power plant efficiency near 35 percent, about 43 gallons of cooling water have to be circulated through the system per kilowatt-hour generated. Thus, the total costs of cooling tower operation, that is, of water recirculation, may be about 0.3 to 0.4 mill per killowatt-hour generated, roughly 5 to 7 percent of generation cost or 2 to 3 percent of combined generation and distribution costs.

The use of greater cooling ranges* (R), a recent trend particularly in large plants employing natural draft cooling towers, has the effect of reducing recirculation cooling costs below these estimates. With a 25-degree cooling range (compared with 15 degrees), recirculation rate is only three-fifths as great, tower size is reduced, pumping energy is decreased, and the total cost of operating the cooling tower system per kilowatt-hour generated is reduced to about eighty percent of the previous values, viz. 0.2 to 0.3 mill per killowatt-hour. Partially offsetting this saving, however, is a reduction in generating capacity and efficiency due to higher condenser temperature, as explained below. The net result of operation at high cooling ranges, (up to 30 degrees recently) in large plants employing cooling towers is a total generation cost per kilowatt-hour typically about 0.2 to 0.3 mill above the cost in a plant using once-through cooling.

Although this discussion and the foregoing cost analysis are based cn the forced-draft type of cooling tower, a comment on the economics of natural draft towers is pertinent. Before 1962, there were no natural draft towers in the U.S., mainly because atmospheric conditions, cooling loads (i.e., power plant size), and costs of construction labor favored the forced draft type. But with the advent of very large generating units of million kilowatt capacity, economic factors tend to shift the balance in favor of natural draft installations. Although substantially higher capital costs are involved (for typical fossil-fuel plants, $7 to $10 per KW investment in natural draft towers compared with $5 to $8 in forced draft towers), costs of operating natural draft towers are lower, mainly because fan power is not used. Investments in both types of towers for nuclear plants are roughly 50 percent higher.

The previously developed cost equations for forced draft cooling towers may be employed with reasonable confidence for appraising natural draft cooling costs if an appropriate "Standard" capital cost (the term I in equation 1) is used and if the term .14K is omitted in equation 2. An approximate value for I may be taken as $12 per gpm. In addition to the factors that determine the

* For crossflow mechanical draft water cooling towers, $10 \leq R \leq 31°F$, and for hyperbolic natural draft crossflow water cooling towers, $15 \leq R \leq 45°F$.

value of K for crossflow mechanical draft water cooling towers, the tower cost of hyperbolic natural draft crossflow water cooling towers, in $ per 1,000 Btu/hr, is also a function of percent relative humidity.

Shade and Smith (14) have made comparative cost estimates for six types of cooling systems under similar conditions. While the costs for any specific project are greatly influenced by local geographic and topographic conditions, this compilation of costs can be used for general comparison.

	Capital cost of cooling system, $ per kilowatt of plant capacity
1. Run-of-River Cooling System	5
2. Bay-Lake Cooling System	6
3. Natural-Draft Cooling Tower; Run-of-River Makeup	7.5
4. Cooling-Pond System	10
5. Natural-Draft Cooling Towers; Reservoir Makeup	11
6. Dry-Cooling Towers	22

These figures are related to I (the capital cost per gpm circulated) by Table 1 in that if the figures are divided by the appropriate value in Table 1, the result is the factor by which K is multiplied to obtain I in equation 1.

ECONOMIC LOSS DUE TO THERMAL DISCHARGE

Considering now the possible economic loss by a downstream power plant forced to use cooling water warmer than that which would have been naturally available had there been no thermal discharge upstream, several factors are involved. Unless the upstream plant has used the entire river flow in its once-through cooling operation, there will be some dilution of the effluent discharge with resulting temperature somewhere between the natural river temperature and that of the heated discharge. Secondly, unless the downstream plant is only a short distance away, there will be temperature decreases in the river prior to subsequent cooling water withdrawal. The rate of cooling is in turn dependent upon atmospheric conditions, river turbulence, solar radiation, and so on. Given sufficient distance of travel, the river will eventually cool to the same temperature, at the far downstream point, as if there were no thermal discharge. Natural conditions may, of course, cause heating of the river rather than cooling, the artificially added heat being superimposed on natural effects.

The results of a downstream power plant using warmer condenser water than would naturally have been available are a decrease in total electrical generation and a decrease in thermal efficiency, hence, an increase in costs per killowatt-hour generated. The net additional capital cost of a power plant due to such temperature increase, C_T, in cents per thousand gallons of water used in the condensers, may be determined by use of the following equation (1),

$$C_T = C_c \left[\frac{-(1 - \eta)\ \beta y\ \Delta T\ dT_1}{36 n_o (1 - \beta\eta)(1 - e^{-yt})\ T_1} \right] \qquad (3)$$

where

C_c = is the basic capital cost of the entire power plant, dollars per killowatt of installed capacity

η = theoretical steam cycle efficiency (Carnot efficiency), decimal

β = turbine - generator efficiency, decimal

y = fractional decrease in plant load factor per year, years^{-1}

ΔT = temperature change in the water stream passing through the condenser, ^0F

dT_1 = temperature increase in the entering cooling water due to thermal discharge upstream, ^0F

n_o = present load factor of the plant (equals electricity generated divided by rated capacity), decimal

t = power plant life, years

T_1 = natural temperature of cooling water, unaffected by thermal discharge upstream, $^0R = {}^0F + 460$.

Ordinarily, $\Delta T = R$. Also, y can be expressed as $\Delta n/\Delta t$. Usually T_1 exhibits a sinusoidal variation during the year (3), and $T_1 + dT_1$ may also exhibit a similar sinusoidal pattern on an annual basis (4). The sum $T_1 + dT_1$ can be evaluated by the methods given in reference 5.

When typical values are substituted in Equation 3, including a temperature rise (ΔT) of 12^0F through the condenser and a 10^0F increase in inlet cooling water temperature (dT_1) due to thermal discharges from one or more upstream power plants, and if power plant investment (C_c) is assumed $125 per KW, the additional capital cost of power generation (C_T) will be about 0.1 cent per thousand gallons of cooling water circulated.

In addition to the capital cost increase found by use of equation 3, there is also a cost increase caused by higher fuel use. The additional fuel required to meet the fixed electrical demand, F_T, in cents per 1000 gallons water used, may be determined by the relationship (1),

$$F_T = \frac{0.00833f\,(1 - \eta)\;\Delta T dT_1}{(\alpha - H)\;T_1 \eta}\;, \qquad (4)$$

where

f = fuel cost, cents per million Btu.

α = boiler efficiency, decimal

H = actual overall efficiency of electricity generation, decimal.

Substitution of typical values in equation (4), including fuel at 25 cents per million Btu., 0.9 boiler efficiency, and 0.32 overall thermal efficiency, the additional fuel cost, F_T, due to a 10 degree rise in cooling water temperature is about 0.12 cent per 1000 gallons circulated. The total cost increase caused by the ten degree rise is thus 0.10 capital cost plus 0.12 fuel cost, or 0.22 cent per thousand gallons of cooling water flow. At a flow rate of about 50 gallons of condenser water per kilowatt-hours generated, the increase in power cost becomes about 0.01 cent per kilowatt-hour. This cost, unless avoided by cooling tower use in the downstream power plant, would represent an increase of about one percent in total generation costs. If, as already found in some locations, river temperatures are artificially raised as much as 20 degrees by thermal discharge, these figures would be doubled.

1. Cootner, P., and Löf, George O. G., Water Demand for Steam Electric Generation, Resources for the Future, Washington, 1965.

2. Managing Waste Heat with the Water Cooling Tower, by Joe Ben Dickey, Jr., and Robert E. Cates, The Marley Company, 222 West Gregory Bent, Kansas City, Missouri 64114, 1970, $5, pages 6-7.

3. "Annual Variation of Stream Water Temperature," by J. C. Ward, Journal of the Sanitary Engineering Division, ASCE, Vol. 89, No. SA6, Proc. Paper 3710, December, 1963, pages 1-16.

4. Discussion of (3), by L. W. Durtis, T. J. Doyle, and G. W. Whetstone, Vol. 90, No. SA4, Proc. Paper 4006, August, 1964, page 96.

5. Publication number IX. (12 and 13).

X. OPTIMIZATION (MINIMUM COST) OF COOLING TOWER DESIGN AND OPERATION

(EXTENDED ABSTRACT)

by

John C. Ward and George O.G. Löf

If, in equations 3 and 4 above, $\Delta T = R$, dT_1 is the approach, and if T_1 is the absolute wet-bulb temperature in ^oR, then the sum of C_T and F_T represents the net additional cost of power plant operation due to greater cooling ranges (R), greater approaches (dT_1), and higher wet-bulb temperatures (T_1). Therefore, the total cost, C_Σ, in ¢ per 1,000 gallons is

$$C_\Sigma = C_I + C_o + C_T + F_T \quad . \qquad (5)$$

For a given location and power plant, the variables that can be varied are: K, R, C, A, and dT_1. In this connection, it should be noted that, from reference 2, $K = f(R, dT_1, T_1)$ for crossflow mechanical draft water cooling towers and $K = f(R, dT_1, T_1, \% RH)$ for hyperbolic natural draft crossflow water cooling towers. These equations illustrate the need for being able to express K in an empirical, mathematical fashion. One might consider, that for a given location and make-up water quality, C and A are given, and hence not variable. If this is the case, then $C_\Sigma = f(R, dT_1)$.

Using $C_1, C_2, \ldots, C_n$ to represent constants for a given location and power plant, then equations 1, 2, 3, and 4 can be expressed as follows for crossflow mechanical draft water cooling towers:

$$C_I = C_1K \quad (1A)$$

$$C_o = C_2R + C_3K + C_4 \quad (2B)$$

$$C_T = C_5RdT_1 \quad (3A)$$

$$F_T = C_6RdT_1 \quad (4A)$$

and equation 5 can be expressed as

$$C_\Sigma = C_4 + (C_1 + C_3)K + R\,[C_2 + (C_5 + C_6)\,dT_1] \quad (5A)$$

For hyperbolic natural draft crossflow water cooling towers, $C_3 = 0$. In addition, the capital cost of these towers is given in $\frac{\$}{10^3\ \text{Btu/hr}}$ as a function of % RH (% relative humidity), R, dT_1, and T_1 (see pages 10 and 11 of reference 2 on page 17 of this report). In order to use equation 1, this cost must be converted to \$/gpm. Therefore,

$$I = \left(\frac{\$}{10^3\ \text{Btu/hr}}\right)\left(\frac{60\ \text{minutes}}{\text{hour}}\right)\left(\frac{\text{Btu}}{\text{kwh}}\right)\left(\frac{\text{kwh}}{\text{gal}}\right)\left(\frac{1}{1{,}000}\right) \quad (6)$$

The quantity of cooling water required per kwh is

$$\frac{\text{gal}}{\text{kwh}} = \frac{\text{heat to be discarded, Btu/kwh}}{(R)(8.34\ \text{lb/gal})[1\ \text{Btu/(lb)}(^oF)]} = \frac{\text{Btu/kwh}}{8.34R} \quad (7)$$

The quantity of heat to be discarded is

$$\frac{\text{Btu}}{\text{kwh}} = 3{,}413\left(\frac{\alpha}{H} - 1\right) \quad (8)$$

Combining equations 7 and 8, one obtains

$$\frac{\text{gal}}{\text{kwh}} = \frac{409}{R}\left(\frac{\alpha}{H} - 1\right) \quad (9)$$

Substituting equation's 8 and 9 into equation 6, the result is

$$I = \left(\frac{\$}{10^3\ \text{Btu/hr}}\right)(0.5\ R) \quad (10)$$

Obviously, R and dT_1 can not be chosen independently, because their sum must always be a constant. In fact, if one uses T_C to represent the temperature of the water from the condensers before cooling, then

$$T_C = T_W + dT_1 + R \qquad (11)$$

where T_W = wet-bulb temperature, ^oF, and T_C and T_W are constants for a given location and power plant. Therefore, for a given location and power plant, one would expect that $\$/(10^3\ \text{Btu/hr})$ could be expressed as a function of R alone or

$$\frac{\$}{10^3\ \text{Btu/hr}} = f(R). \qquad (12)$$

Therefore equation 10 becomes

$$I = 0.5\ R\ f(R) \qquad (10A)$$

and the equivalent equation 1A becomes

$$C_I = C_7 I = C_7\ R\ f(R)/2 \qquad (1B)$$

Substitution of equation's 1B, 2B, 3A, and 4A into equation 5 gives

$$C_\Sigma = C_4 + R[C_2 + C_7\ f(R)/2 + dT_1(C_5 + C_6)] \qquad (5B)$$

Equation 11 can be solved for dT_1, and then substituted into equations 5A and 5B to give, respectively

$$C_\Sigma = C_4 + (C_1 + C_3)K + [C_2 + (C_5 + C_6)(T_C - T_W)]R - (C_5 + C_6)R^2 \qquad (5C)$$

and

$$C_\Sigma = C_4 + [C_2 + C_7\ f(R)/2 + (C_5 + C_6)(T_C - T_W)]\ R - (C_5 + C_6)R^2 \qquad (5D)$$

The cooling cost is the product of equation's 5C or 5D and 9

$$¢/\text{kwh} = \left(\frac{C_\Sigma}{1,000}\right)\left(\frac{\text{gal}}{\text{kwh}}\right) = \left(\frac{C_\Sigma}{R}\right)(0.409)\left(\frac{\alpha}{H} - 1\right) \qquad (13)$$

Therefore, equations 5C and 5D become, respectively

$$¢/kwh = (0.409)(\frac{\alpha}{H} - 1)\ \{[C_4R^{-1} + (C_1 + C_3)KR^{-1} + [C_2 + (C_5 + C_6)(T_c - T_w)] - (C_5 + C_6)R\} \quad (5E)$$

and

$$¢/kwh = (0.409)(\frac{\alpha}{H} - 1)\ \{C_4R^{-1} + [C_2 + C_7\ f(R)/2 + (C_5 + C_6)(T_c - T_w)] - (C_5 + C_6)R\} \quad (5F)$$

For a given location and power plant, it is clear that

$$K = F(R) \quad (14)$$

Equations 5E and 5F give the cooling costs for crossflow mechanical draft water cooling towers and for hyperbolic natural draft crossflow water cooling towers respectively. One can find the value of R that makes these costs minimums by trying several values of R and plotting the results or analytically. In order to obtain the minimum cost value of R analytically, it is first necessary to obtain an empirical expression for equations 12 and 14, and substitute these empirical results into equations 5E and 5F respectively. The resulting equations can be differentiated with respect to R , and the resulting differential can be set equal to zero to obtain the minimum cost value of R. If the value of R obtained makes the second derivative positive, the value of R gives the minimum cost. The following example illustrates the use of both techniques.

EXAMPLE

Assume that:

r = 0.065 per year
t = 33 years
P = 0.02 per year
N = 0.5
C = 9
Y = 150 mg/ℓ (as $CaCO_3$)
Wa = 1¢/1,000 gallons
A = 50 feet
p = 0.5¢/kwh
C_c = $150/KW
β = 0.9
y = 0.03 per year
n_o = N = 0.5
T_1^o = T_w + 460 = 530°R
H = 0.4
α = 0.9

$\eta = H/\beta\alpha = 0.494$
$f = 25¢/10^6$ Btu
$T_w = 70^oF$

$$C_1 = 8(\frac{r + 1/t + P}{5.256N}) = 8C_7$$

$$= (8)(0.0439) = 0.351¢/1,000 \text{ gallons}$$

$$C_2 = (0.001)\ (\frac{C}{C-1})\ (0.033Y + 17/C + Wa)$$

$$= 8.82 \times 10^{-3}\ ¢/(1,000 \text{ gallons})(^oF)$$

$$C_3 = 0.14p = 0.07\ ¢/1,000 \text{ gallons}$$

$$C_4 = 0.005A\ p = 0.125\ ¢/1,000 \text{ gallons}$$

$$C_5 = C_c\ \{\frac{-(1-\eta)\beta y}{36\eta_o(1-\beta\eta)[1-\exp(-yt)]T_1}\}$$

$$= -\ 6.15 \times 10^{-4}\ ¢/(1,000 \text{ gallons})(^oF)^2$$

$$C_6 = \frac{0.00833f(1-\eta)}{(\alpha-H)\ T_1\ \eta} = 8.07 \times 10^{-4}\ \frac{¢}{(1,000 \text{ gallons})(^oF)^2}$$

$C_7 = 0.0439\ ¢/(1,000$ minutes)($). Further assume that: $T_c = 110^oF$. Substitution of these values into equations 5E and 5F give, respectively

$$¢/kwh = 8.44 \times 10^{-3} - 0.981 \times 10^{-4}\ R + 0.0638\ R^{-1} + 0.215KR^{-1}$$

and

$$¢/kwh = 8.44 \times 10^{-3} - 0.981 \times 10^{-4}\ R + 0.0638\ R^{-1} + 0.0112\ f(R)\ .$$

It will be observed that both equations are the same with the exception of the last term on the right. Table 2 gives the value of K for 70^oF wet bulb and $dT_1 + R = 40^oF$. In addition values of f(R) are given for 50% RH. From the data in this Table (columns 2 and 4),

$$\frac{\Delta f}{\Delta R} \cong -0.0409 + 0.00390\ R$$

and

$$f(R) \cong 1.487 - 0.0409\ R + 0.00195\ R^2$$

Also (from columns 2 and 3),

$$\frac{\Delta K}{\Delta R} \cong -\ 0.12 + 0.00869\ R$$

and

$$K(R) \cong 1.32 - 0.12\ R + 0.00434R^2.$$

Combining the above equations for K and f(R) with the 2 preceding equations for ¢/kwh, one obtains, respectively,

$$¢/kwh = - 0.01736 + 0.0008359R + 0.3478/R$$

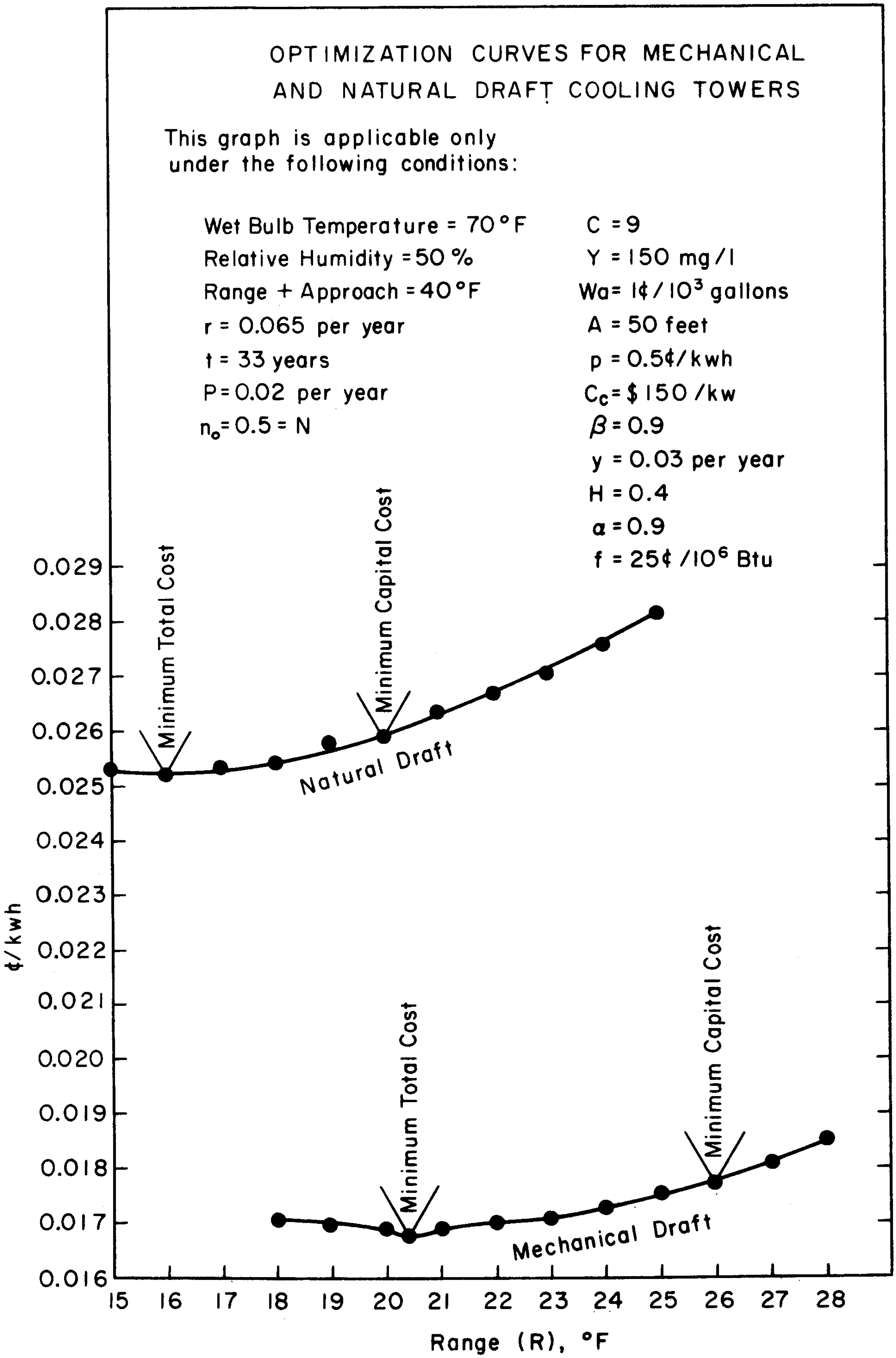
for mechanical draft cooling towers and

$$¢/kwh = 0.02508 - 0.0005571 R + 0.0638/R + 0.0000218 R^2$$

for natural draft cooling towers. Both of these equations are plotted on the following graph. The value of R that makes the total cost a minimum for mechanical draft cooling towers is 20.4°F, so the minimum cost at this value of R is 0.01672 ¢/kwh. It will be noted that the use of the optimization technique developed in this report results in a reduction of cooling costs by 0.00096 ¢/kwh or roughly 6%. Using a figure of 1.482 ¢/kwh as the cost of electricity to the consumer, it is apparent that prevention of thermal pollution would increase the consumer's electric bill by only about 1%.

Table 2 - Cost of preventing thermal pollution

dT_1, °F	R, °F	K	f(R), $\frac{\$}{10^3 \text{ Btu/hr}}$	Cost of preventing thermal pollution ¢/kwh	
				Mechanical Draft	Natural Draft
1	2	3	4	5	6
12	28	1.37		0.01849	
13	27			0.01804	
14	26	1.12		0.01768	
15	25		1.75	0.01751	0.02814
16	24	0.95		0.01724	0.02754
17	23			0.01708	0.02706
18	22	0.78		0.01700	0.02668
19	21			0.01690	0.02632
20	20	0.67	1.45	0.01688	0.02588
21	19			0.01694	0.02574
22	18	0.57		0.01705	0.0254
23	17				0.0253
24	16				0.0252
25	15		1.26		0.0253



OPTIMIZATION CURVES FOR MECHANICAL AND NATURAL DRAFT COOLING TOWERS
This graph is applicable only under the following conditions:
Wet Bulb Temperature = 70 °F
Relative Humidity = 50 %
Range + Approach = 40 °F
r = 0.065 per year
t = 33 years
P = 0.02 per year
n_o = 0.5 = N
C = 9
Y = 150 mg/l
Wa = 1¢/10^3 gallons
A = 50 feet
p = 0.5¢/kwh
C_c = $150/kw
β = 0.9
y = 0.03 per year
H = 0.4
α = 0.9
f = 25¢/10^6 Btu
Minimum Total Cost
Minimum Capital Cost
Natural Draft
Minimum Total Cost
Minimum Capital Cost
Mechanical Draft
¢/kwh
0.029
0.028
0.027
0.026
0.025
0.024
0.023
0.022
0.021
0.020
0.019
0.018
0.017
0.016
15
16
17
18
19
20
21
22
23
24
25
26
27
28
Range (R), °F

XI.

ABSTRACT OF THESIS

SURFACE WATER HEAT BALANCE EXPERIMENTS

This thesis is an investigation of the relationship between the mass-transfer coefficient k_y[lb/(hr)(ft^2)] and wind velocity W (mph). Average values of k_y and $\bar{W}$ were computed for ten different locations distributed over the United States. The energy-budget method was then used to calculate the surface water evaporation from an experimental (solar) pond and to establish a relationship between k_y and W. The use of the energy-budget method was then extended, with slight modifications, to compute the evaporation and k values for fixed nozzle spray droplets, using a No Drag Model. A relationship between k_y and resultant droplet velocity (resultant of initial droplet velocity and wind velocity) was then established.

To be able to use the technique employed in calculating k_y, a sine curve was constructed (with a correlation coefficient of 0.8626) to compute average monthly wind velocities from the known annual average wind velocities in the United States. A contour map was constructed for the annual average wind velocities in the U.S.

An empirical equation was developed to correlate the actual effective sky temperature, to which the water is radiating, with the partial vapor pressure of water in the air, $\bar{p}_a$ and the rate of gain of solar radiation, q_s.

It was found that, except for very short intervals of time, evaporation can be predicted within 10% accuracy by using the energy-budget method. It was also found that k_y for nozzles for a No Drag case was about the same as the k_y calculated using friction, for values of time of rise of the particle to the apex $\leq$ 1 second.

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September, 1971

Betty, please look in Annual Reports for FY77, 78 and 79 and update this list. You only need to list number of students. Don't do the side that's crossed off.

Update

COLORADO STATE UNIVERSITY

STUDENTS ASSISTED BY P.L. 88-379 FUNDS

F.Y.	Number of Graduate Students Supported in part by P.L. 88-379 Funds	Number Employed in Water Resources Field upon Graduation			
		Federal Agency	State Agency	Other	Total Number
1971	70	5	2	6	13
1972	43	2	8	13	23
1973	44	3	1	9	13
1974	47	14	2	13	29
1975	48	2	2	9	13
1976	49	2	0	8	10
1977 - 34					
1978 - 26					
1979 -					
TOTAL	~~301~~	28	15	58	91