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a method for estimating thermal anomaly areas from hot discharges in estuaries

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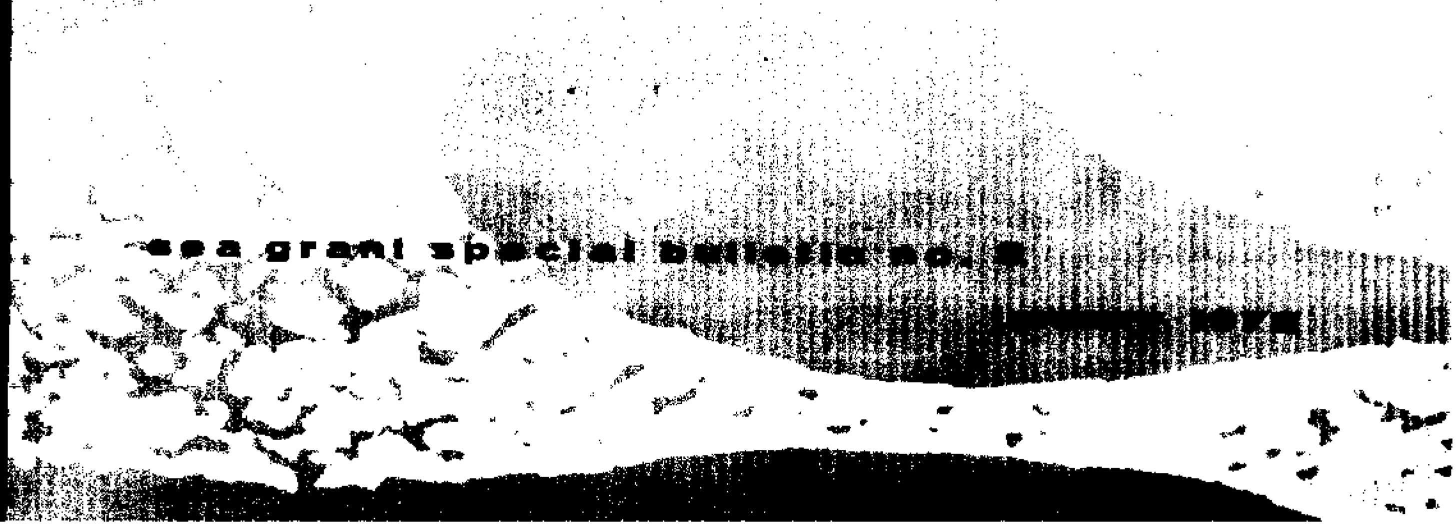

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A Method for Estimating Thermal Anomaly Areas from Hot Discharges in Estuaries

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PREFACE

The Sea Grant Colleges Program was created in 1966 to stimulate research, instruction, and extension of knowledge of marine resources of the United States. In 1969 the Sea Grant Program was established at the University of Miami.

The outstanding success of the Land Grant Colleges Program, which in 100 years has brought the United States to its current superior position in agricultural production, was the basis for the Sea Grant concept. This concept has three objectives: to promote excellence in education and training, research, and information services in the University's disciplines that relate to the sea. The successful accomplishment of these objectives will result in material contributions to marine oriented industries and will, in addition, protect and preserve the environment for the enjoyment of all people.

With these objectives, this series of Sea Grant Special Bulletins is intended to convey useful research information to the marine communities interested in resource development.

While the responsibility for administration of the Sea Grant Program rests with the Department of Commerce, the responsibility for financing the program is shared by federal, industrial and University of Miami contributions. This study, A Method for Estimating Thermal Anomaly Areas from Hot Discharges in Estuaries, is published as a part of the Sea Grant Program.

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A METHOD FOR ESTIMATING THERMAL ANOMALY AREAS FROM HOT DISCHARGES IN ESTUARIES

ABSTRACT

A graphic approach for the prediction of thermal anomaly areas from hot discharges is presented to provide a tool for power plant design considerations. The determination of temperature deviations from ambient, based on energy conservation principles, can be conducted with much greater precision than prediction of absolute temperatures. Input data for the graphic procedure are discharge rate and temperature anomaly. In addition, characteristic ambient temperature and wind conditions must be specified.

INTRODUCTION

The accurate prediction of water temperatures in estuaries under different thermal loading conditions is hampered by several fundamental difficulties; first, basic knowledge of the heat transfer processes is only qualitatively satisfactory. But even with a perfect quantitative theory, the number of parameters influencing the problem and which have to be observed or themselves predicted, precludes precise analysis without a substantial data gathering effort. It is frequently of interest to consider not the actual temperature, but its deviation from what it might have been without the thermal discharge under consideration. A perturbation analysis is now being undertaken. This is a task which can be carried through in general with a much greater degree of precision than the determination or prediction of absolute temperatures. If, as is frequently the case, one is primarily concerned with the problem under conditions where the environmental mean temperature is already quite high, the task is further simplified due to the increasing predominance of evaporation as the main cooling process.

ESTIMATION OF THERMAL ANOMALY AREAS

The graphical approach to the determination of heated areas which is presented herein is intended to provide a first quick-look guidance in design considerations. Because it deals only with the prediction of surface area associated with certain thermal anomaly levels, it cannot be used alone for the consideration of problems where, for example, ecological impact on bottom-dwelling, benthic communities is involved. The basic physical concept underlying the approach is that since the cooling is a surface process, the rate of heat loss, which has to balance the excess thermal loading, depends only on the surface area distribution of thermal anomaly, and not at all on the thickness of the warm layer. The latter only adds thermal inertia to the system, i.e., determines rate of reaction to changes in loading, or ambient conditions.

The prediction of water temperature is based on the principle of thermal energy conservation, expressed as a balanced heat budget, where various physical processes acting on the system are identified by corresponding items in the balance sheet. By considering a shallow layer of water, perhaps of variable depth, flowing out from a source at a discharge rate q (volume/unit time), and with some initial temperature T, the problem of combining the ensuing variable velocity distribution with temperature change predictions into a theory for the distribution of temperature anomalies seems a formidable task at first sight. However, some simple physical considerations suggest that one part at least of the problem may be simpler than expected. Consider what happens to the temperature of flowing water, if a constant rate of heat transfer occurs at the top surface. The heat capacity of column is proportional to the depth. The rate of cooling of the water, like the flow velocity at fixed discharge rate, is thus inversely proportional to the depth. It follows that the downstream temperature gradient is uniform, and independent of the local depth, and flow velocity. Now a general formulation extending this argument to arbitrary flow geometries is presented.

A steady state flow pattern, where an initial temperature anomaly decreases gradually away from the source is first assumed with the steady temperature field described by a set of isothermal curves. If the vertically averaged vector velocity is V, and the component perpendicular to the local isotherm is V_n, then the total volume flow across the isotherm is:

$$q = \int_{T = \text{const}} hV_n ds \tag{1}$$

where h is the local depth, q the prescribed discharge rate and T is a constant temperature. Heat flow continuity suggests that we can write:

$$\frac{\partial q\ (T-T_a)}{\partial A} = H(U,\ T-T_a) \qquad (2)$$

where A is the surface area enclosed by a particular isotherm, U is the wind speed defined at a suitable reference level, T is the surface temperature and T_a is the ambient equilibrium temperature. Here $H(U,\ T-T_a)$ is the sum of the turbulent transfer processes of evaporation and sensible heat flux. The bulk transfer coefficient method of estimating the fluxes is used (Kraus, 1969).

The evaporation Q_E and sensible heat flux Q_s are written:

$$Q_E = C_D U L \rho_{sw} \frac{\partial \ln\rho_{sw}}{\partial T} (T-T_a) \qquad (3)$$

$$Q_s = C_D U c_p \rho_a\ (T-T_a) \qquad (4)$$

with C_D = drag coefficient (1.3×10^{-3}), c_p is the specific heat of air at constant pressure p (0.240 Cal/g°C), L is the latent heat of evaporation of water, ρ_a is the density of air at ambient temperature and pressure, and ρ_{sw} is the saturation water vapor density at T. Thermodynamic water properties were taken for fresh water, considering that salinity effects in this problem are not important. Since $H = Q_E + Q_s$ we can write equation (2) as:

$$\frac{\partial q(T-T_a)}{\partial A} = C_D U \left[c_p \rho_a + L\rho_{sw} \frac{\partial \ln\rho_{sw}}{\partial T}\right](T-T_a) \qquad (5)$$

Since q is a constant this can be rewritten as:

$$\frac{d\ln(T-T_a)}{dA} = \frac{C_D U}{q} \; Q(T) \qquad (6)$$

where $Q(T) = c_p \rho_a + \frac{L\rho_{sw}}{16}$

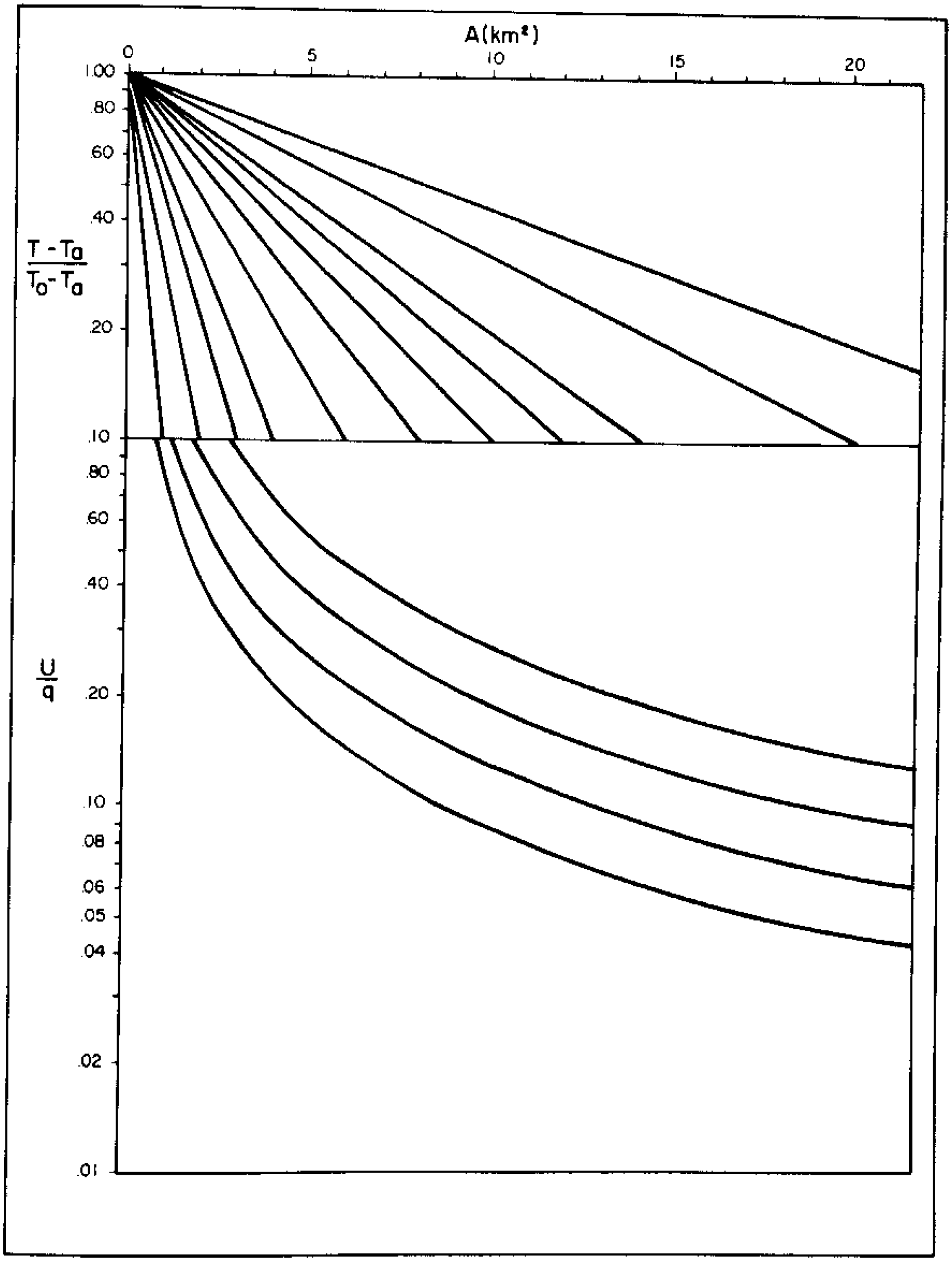
and we have taken: $\frac{\partial \ln\rho_{sw}}{\partial T} = (16^oC)^{-1}$

Integration of equation (6) yields:

$$\ln\left[\frac{T-T_a}{T_o-T_a}\right] = \frac{C_D UA}{q} \; Q(T) \qquad (7)$$

which is the desired form for estimating the thermal anomaly area A associated with some temperature T given an initial temperature above ambient T_o, discharge rate q, ambient equilibrium temperature T_a and wind speed U. Convenient numbers near unity are produced from equation (7) by expressing U in m/sec, q in m^3/sec and A in km^2, since both Q(T) and C_o are of order 10^{-3}.

A useful method for determination of heated areas from equation (7) is presented in the nomogram shown in FIGURE 1. The effect of variations in the ambient equilibrium temperature of the receiving water body, i.e., variations in Q(T), are accounted for in the bottom half of the figure. An increase in the ambient temperature will substantially increase the heat transfer to the atmosphere by evaporation, which is seen to have a great effect on thermal area predictions, especially during weak wind

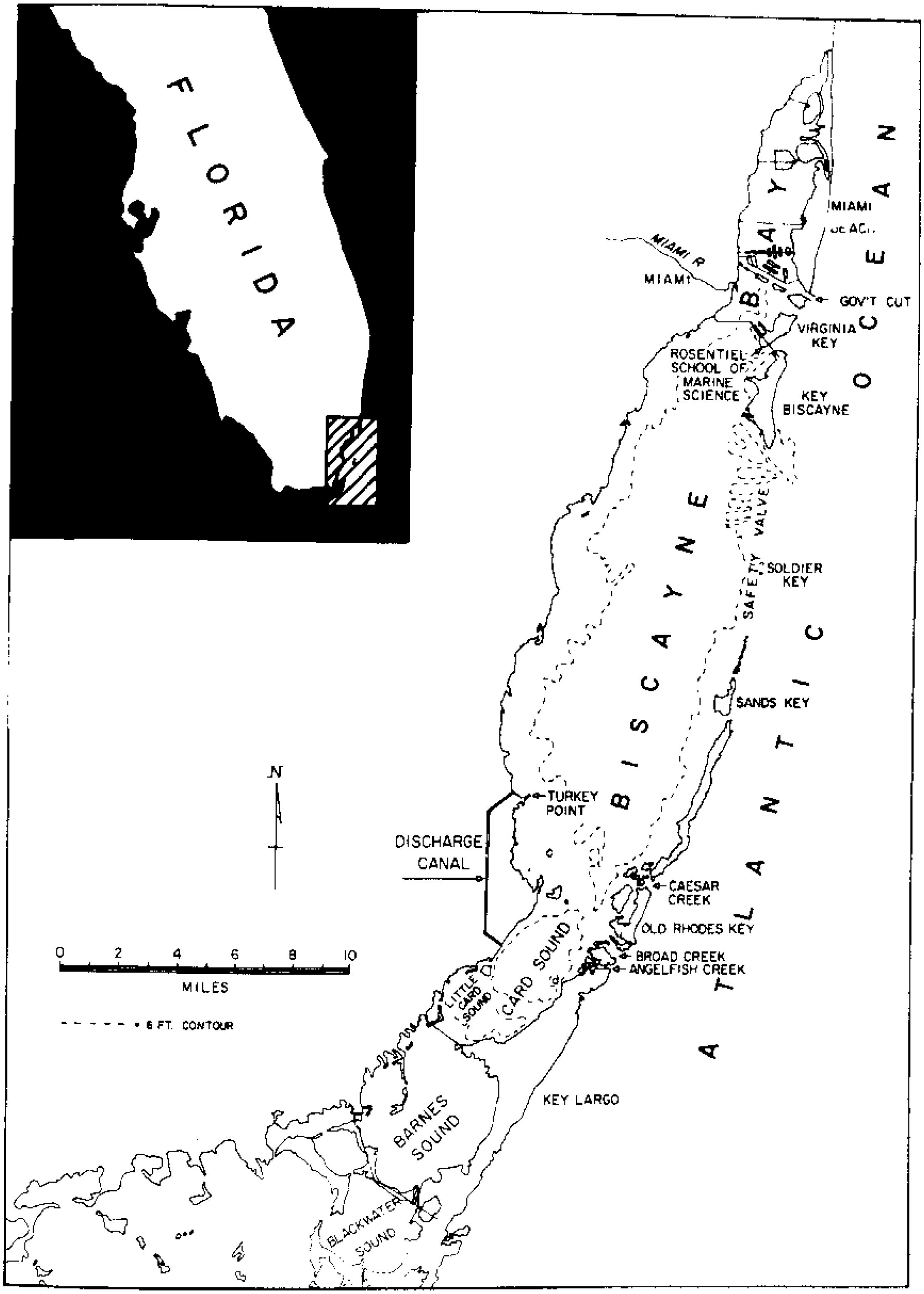


Estimation of thermal anomaly areas from hot discharges.

FIG. 1

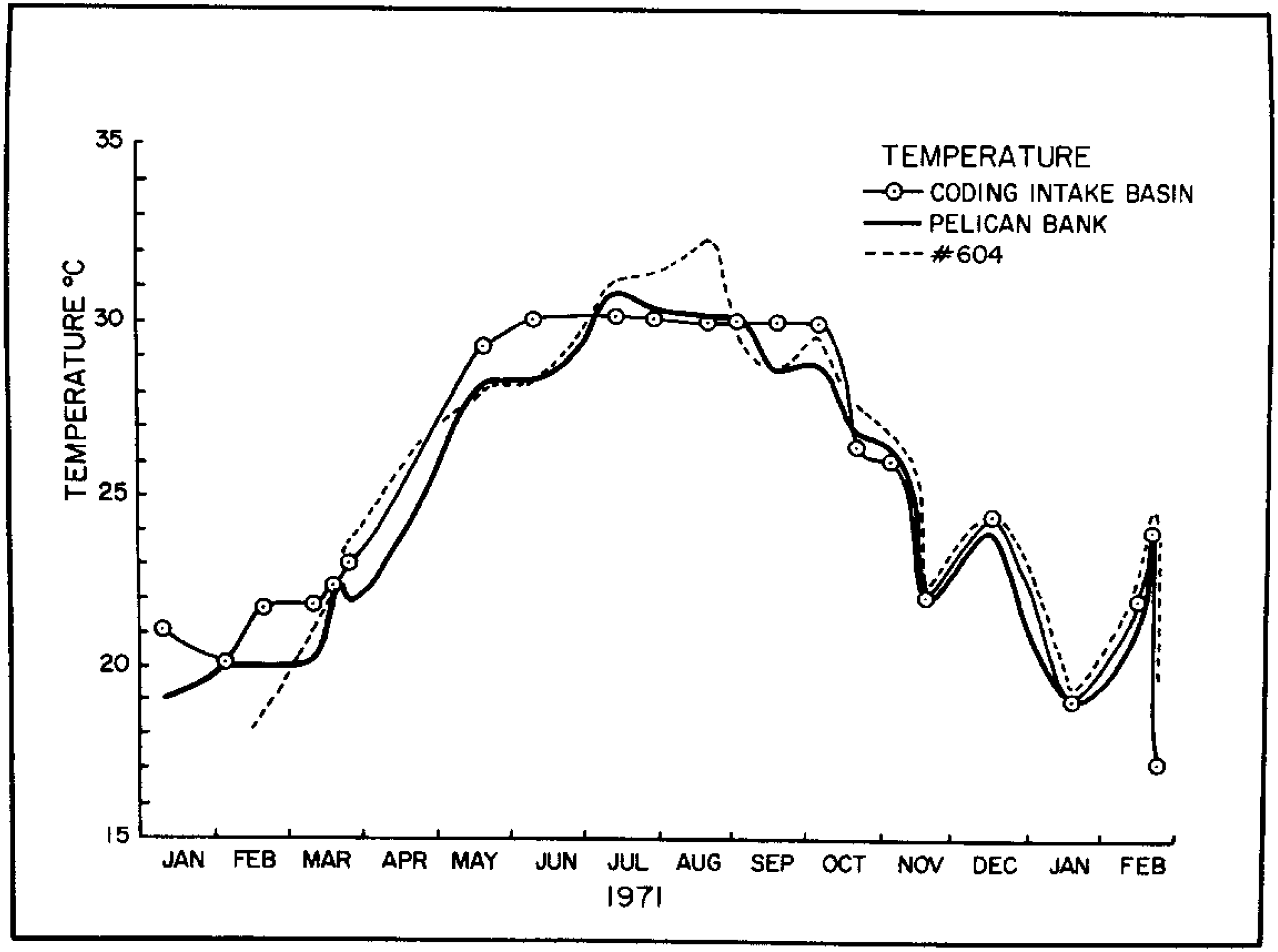
periods. The suitable choice of wind speed, discharge rate and ambient temperature will define a line in the upper half of the figure from which the area associated with some fraction of the initial temperature anomaly $\frac{T-T_a}{T_o-T_a}$ can be found.

The use of this nomogram will be described taking the planned discharge of thermal effluent into Card Sound, Florida as an example. Florida Power and Light Corp. is nearing completion of two 760 megawatt nuclear units which are planned to be put on line with the two existing fossil fuel units at Turkey Point during the summer of 1972. The thermal effluent produced from cooling waters brought in from south Biscayne Bay will be discharged into Card Sound (FIGURE 2) with daily average volume flow and initial temperature above ambient of approximately 2800 ft^3/sec (78 m^3/sec) and 3-4°C respectively. A comparison of seasonal fluctuations in the ambient surface temperature of south Biscayne Bay and Card Sound during 1971 is shown in FIGURE 3. The use of the nomogram is shown in FIGURE 4. Considering for the critical summer period an ambient equilibrium bay temperature of 30°C and a wind speed of 10 knots (5m/sec) one will enter the lower half of FIGURE 4 at $U/q = 0.064$ and continue on a straight line to the 30°C curve. From this point one enters the upper half of the figure along a vertical line. A line drawn from the intersection of this vertical line with the upper half of the figure to the upper left hand corner, i.e., where $\frac{T-T_a}{T_o-T_a} = 1.00$ will define the thermal anomaly area associated with some fraction of the initial temperature above ambient.



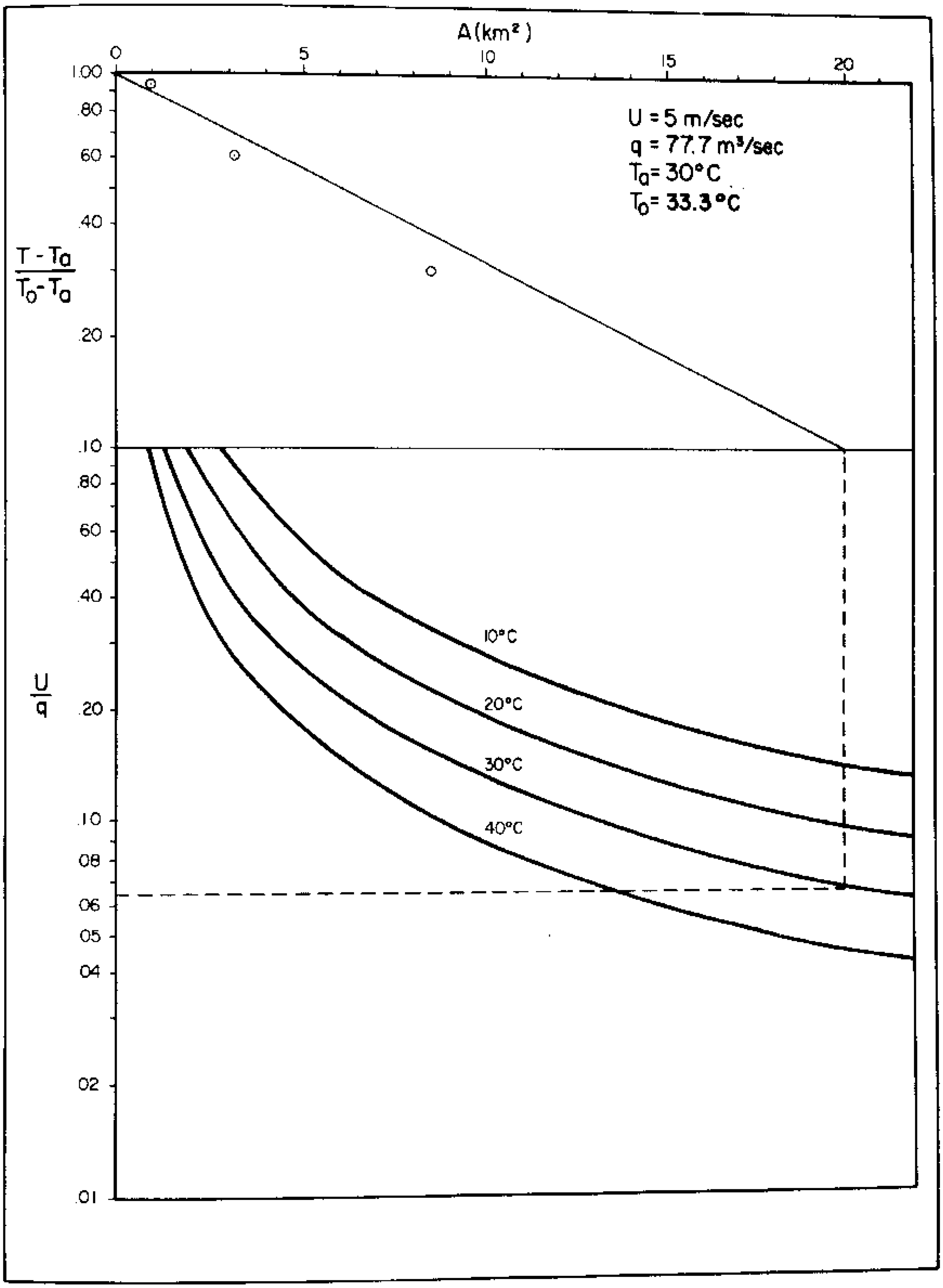
Biscayne Bay and Card Sound.

FIG. 2



Temperature time series of south Biscayne Bay and Card Sound for 1971.

FIG. 3



Method of estimation of thermal anomaly areas.

FIG. 4

The solid points shown in this figure represent actual measurements of the thermal plume into south Biscayne Bay during a plant testing period when the flow rate and initial temperature were equal to the example considered here. The measurements were obtained with a surface mapping technique using a Bissett-Berman Thermosalinograph with a flow-through pumping system in a rapid boat. Thermal anomaly areas associated with this example are presented in TABLE 1 and are compared to the measured areas.

TABLE 1

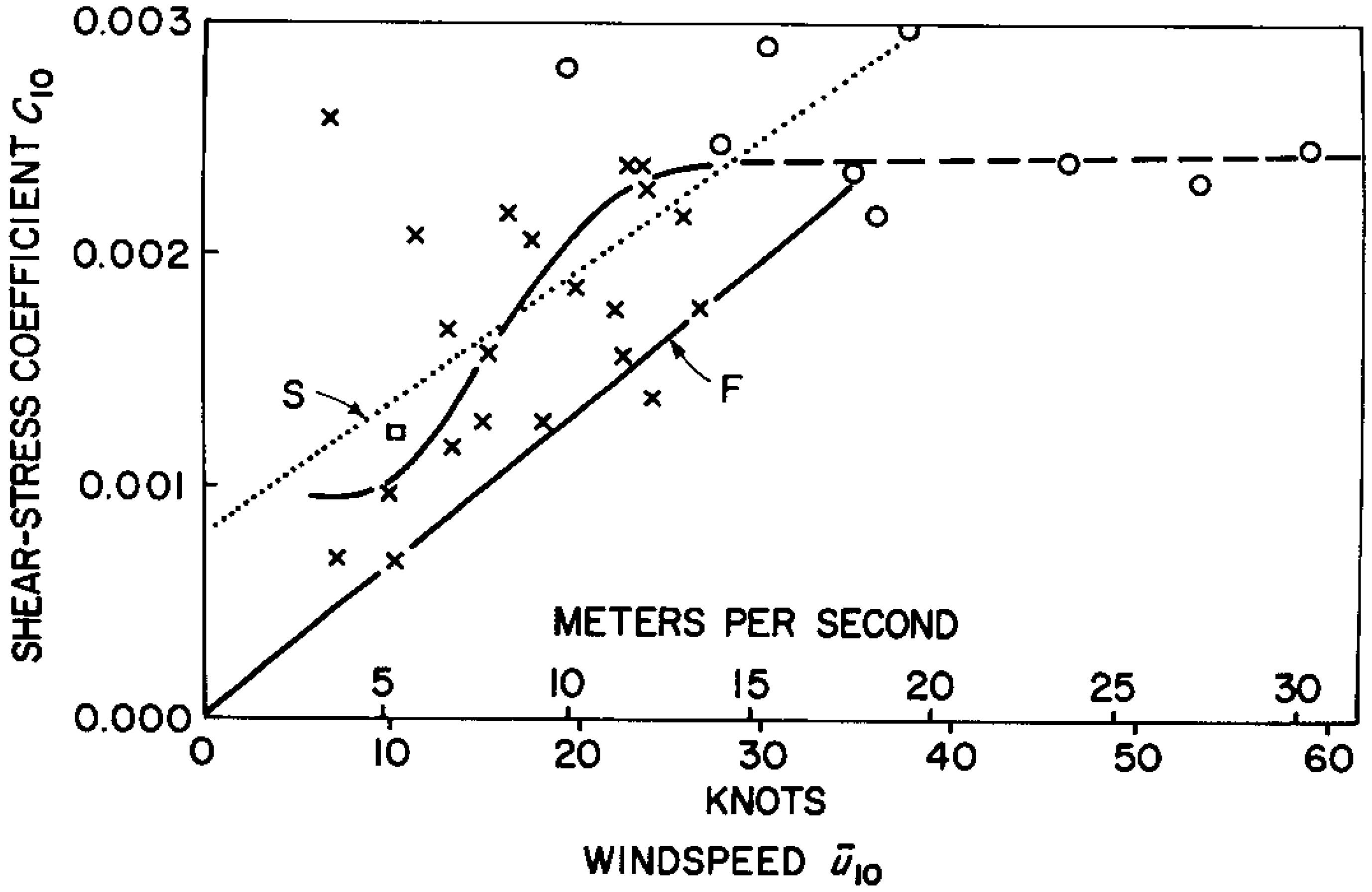
ESTIMATION OF THERMAL ANOMALY AREAS
FROM HOT DISCHARGES WITH
$U = 5$ m/sec; $q = 77.7$ m^3/sec; $T_a = 30^\circ$C; $T_o = 33.3^\circ$C

$^\circ$C Above Ambient	$\frac{T-T_a}{T_o-T_a}$	Predicted Area (km^2)	Measured Area (km^2)
3	.91	0.80	0.92
2	.60	4.50	3.17
1	.30	10.50	8.28

FIGURE 4 and TABLE 1 indicate that the thermal area predictions overestimate the measured areas by approximately 25%. This is a reasonable accuracy for initial estimates during site selection and power plant design stages. The uncertainties of the method are largely due to uncertainties in the drag coefficient, since the area predictions are inversely proportional to C_D. FIGURE 5, taken from Roll (1965), shows the fluctuating nature of this coefficient with wind speed. For light winds the data of Deacon, et.al. (1956) indicates that 1.3×10^{-3} is a reasonable value for C_D; however, for winds on the order of 20 knots or greater, a value of 2×10^{-3} may be more appropriate. It should also be pointed out that this analysis is for steady state conditions, which are achieved in approximately 24 hours in the Card Sound example. Therefore, the initial discharge temperature must represent an average over a sufficient time duration to remove temporal fluctuations.

SUMMARY

A method is presented for the estimation of thermal anomaly areas from heated discharges using a graphic approach. Inputs to the method are the wind speed, measured at some reference height; the discharge flow rate; the ambient equilibrium temperature of the receiving water body; and the initial temperature at the point of discharge. The usefulness of the graphic approach lies in its simplicity and ease of operation. The method can serve as an effective tool to aid power plant designers, state and local officials, as well as concerned conservation groups in site selection and proper design to fit the local environment.



Shear-stress coefficient C_{10} for wind action at the sea surface depending on the wind velocity $\overline{U}_{10}$ (From Francis, 1959). Origins of presented data: straight solid line; F. Francis (1951) (wind tunnel experiments); 0, Hellström (1953); □, charnock et al., (1959); x, Deacon et al., (1956).

FIG. 5

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