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A METHOD FOR PREDICTING THE PERFORMANCE OF NATURAL DRAFT COOLING TOWERS

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A METHOD FOR PREDICTING THE PERFORMANCE

OF

NATURAL DRAFT COOLING TOWERS

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ABSTRACT

A method is developed for analyzing the performance of counterflow and crossflow natural draft cooling towers that does not assume saturated air at the top of the packing. Types of cooling towers and the principles of operation are considered. Simplified differential equations for the heat and mass transfer relations and the methods of integrating them for both counterflow and crossflow towers are given. A large number of integration steps is shown to be unnecessary. Equations for estimating the pressure losses in the tower are also given. Simplified flow charts using these integration schemes show how the computer program is used to evaluate tower performance. The computed performance of towers of various heights operating in moist and in dry conditions is shown. The effect of inlet water temperature is shown to be significant. Finally, the computed performance of a given tower with fixed inlet water temperature is shown as a function of relative humidity and dry bulb air temperature.

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CONCLUSIONS

The mathematical model is capable of yielding reliable predictions of cooling tower performance at relatively low cost. Inasmuch as the state of the air leaving the packing is actually determined and not merely assumed to be saturated, the program results will be of value in studying the effect of a tower on local atmospheric conditions.

When the atmospheric conditions are such that the air becomes saturated before it reaches the top of the packing, the integration scheme is modified slightly so that the program will not predict a supersaturated condition. This condition might arise when the bulk air becomes saturated and its total heat is less than the total heat of the thin layer of saturated air next to the water and at the water temperature. Water vapor can still be transferred to the bulk air by virtue of this driving potential, but the program assumes that the bulk air cannot be supersaturated. Therefore, the program forces part of the excess water vapor to condense into droplets and the temperature of the mixture of saturated air and water droplets to increase until the total energy of the mixture is the same as the bulk air is at 100 percent saturation.

Tower performance is very sensitive to the values of the heat transfer and friction coefficients. An option in the program makes it relatively easy to change the equations predicting these coefficients to conform to different types of packings. Because the program computes the actual velocities at different sections in the tower, these relationships can be based on the local velocity. Therefore, the coefficients can be varied in the mathematical model just as they vary in the actual tower.

The degree to which the performance predicted by the model conforms to that of an actual tower depends on how well the input data used in the program match those of the actual tower. Therefore, final verification of the model awaits the acquisition of reliable test data on actual towers for which the inlet and packing geometry is known. These data are especially needed to estimate heat transfer and friction coefficients.

SECTION I

COOLING TOWER TYPES

Cooling towers are merely heat exchangers that transfer heat from water to air. Dry towers perform this function without direct air-water contact and rely solely upon heat transfer by convection. Wet towers use direct air-water contact, with energy transfer by evaporation being the predominant exchange mechanism, and convection playing a minor role. To promote evaporative and convective cooling, wet towers require large water surface areas and high airflow rates. Large water surface areas are produced by distributing the warm water over packing that either breaks the water into small droplets (splash packing) or allows the water to flow downward in thin films (film packing). Airflow can be produced with fans or natural drafts. In either case, the tower and packing can be designed to operate with the air flowing upward through the packing (counterflow) or horizontally across the packing (crossflow). This paper is concerned only with the wet, natural draft cooling tower.

A natural draft cooling tower is basically a large chimney that provides a draft to pull air over a large surface of water. Either heating the air or increasing its vapor content will decrease its density, and it will rise. Thus, airflow is established without the expenditure of external power. This is an important advantage for natural draft towers, because the mass rate of airflow required is of the same order as the mass rate of waterflow which, for large heat sources like nuclear power plants, may be equivalent to a small river, e.g., 1000 cfs.

Natural draft towers are usually constructed from reinforced concrete and because of their large height are hyperbolic in profile for greater structural strength. Figures 1 and 2 show the basic components of counterflow and crossflow towers.

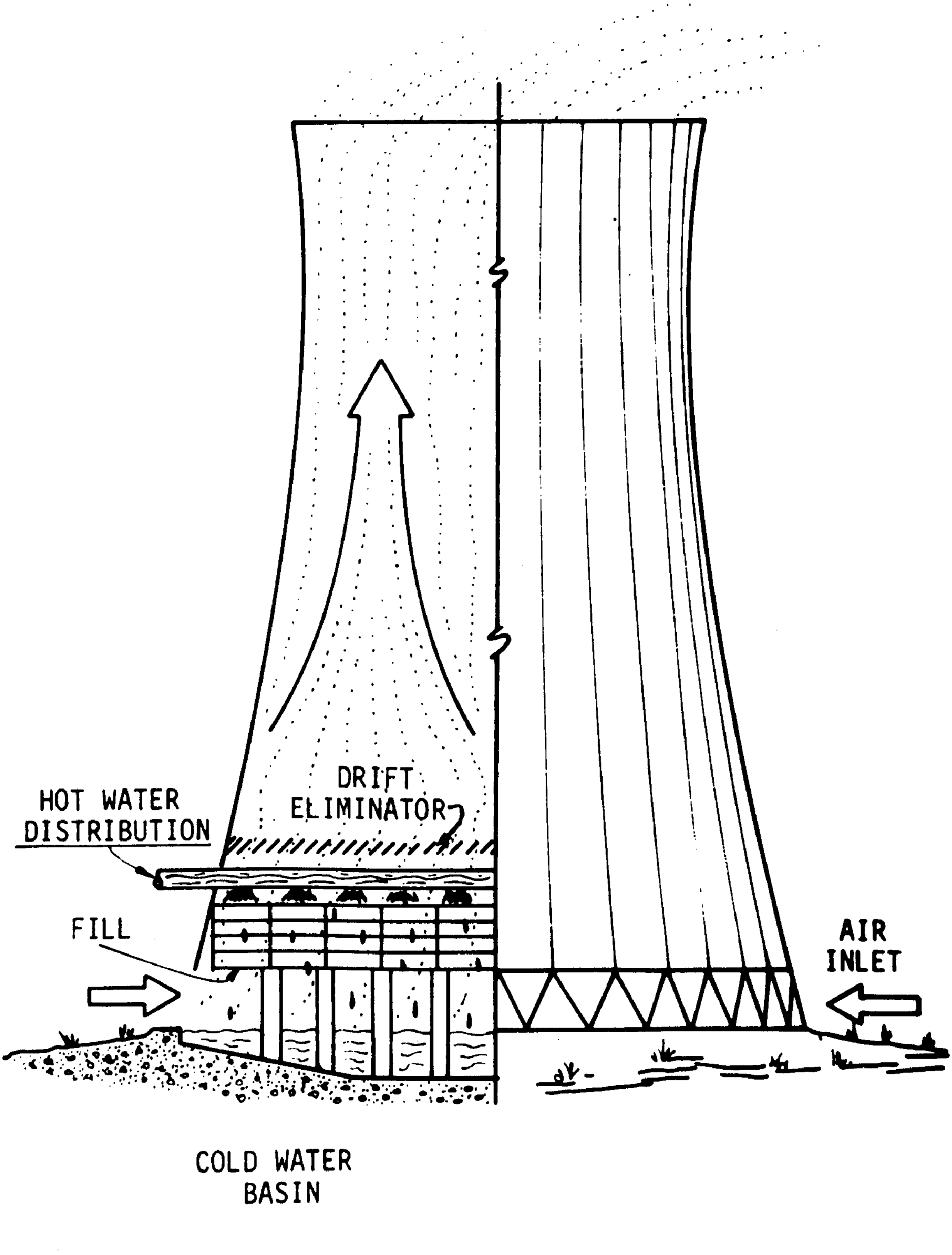

FIG. 1 COUNTERFLOW TOWER

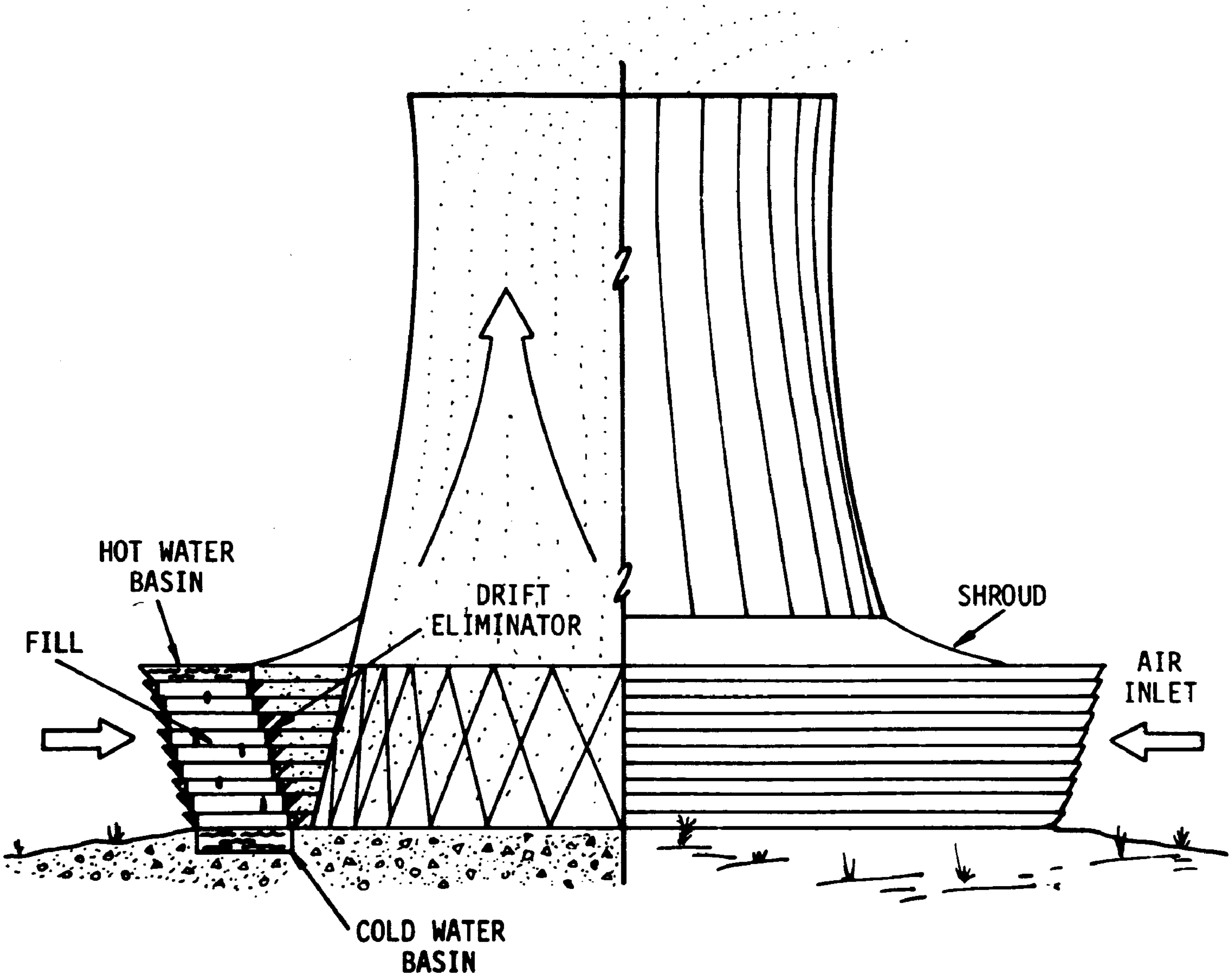

FIG. 2 CROSSFLOW TOWER

SECTION II

PRINCIPLES OF TOWER OPERATION

Figure 3 provides information leading to a basic understanding of how a natural draft cooling tower operates. This psychrometric chart contains the same information as the Carrier psychrometric chart that is frequently employed in the United States, but presents the data in a form that can be used more directly in cooling tower calculations. The left vertical scale is the total heat of the moist air, which is the quantity that governs energy exchange for the combined sensible and latent heat transfer. Inasmuch as the total heat depends almost entirely on the wet-bulb temperature, the total heat scale may also be interpreted as a suitably graduated scale of wet-bulb temperatures, as is illustrated by the right-hand vertical scale. The abscissa is the dry-bulb temperature. The state of moist air can be found on the diagram by any two of the following three quantities: wet-bulb temperature, dry-bulb temperature, and relative humidity. The specific volume lines refer to the true specific volume of the mixture (reciprocal of the density) in ft^3/lb of mixture. This is useful in calculating the difference in density between two points in the tower and thus determining the draft through the tower.

Even though the variables are related through the heat and mass transfer relations in a rather intricate manner, inspection of Figure 3 can yield a qualitative picture of the effect of some of the variables on tower performance. For example, Figures 4 and 5 which are similar to Figure 3, but with much of the psychrometric data removed for clarity, show how the state of the air and the temperature of the water change as they move through the packing in a counterflow tower.

Although the type of psychrometric chart (Figure 3) used in this paper has been suggested by others, Wood and Betts (6,7) appear to be the first to publish it. Also, Figures 4 and 5 are based upon similar curves by Wood and Betts.

If one assumes that the water is at the same temperature as the layer of saturated air next to it, the locus of points indicating the change in water temperature as it flows down through the packing is represented in Figure 4 by the saturation line T-S-R-Q. Thus the water is cooled from θ_2 to θ_1. The line A-B-C-D-E shows the character of the air as it flows up through the packing, where point A represents the state of the incoming air. The state of the

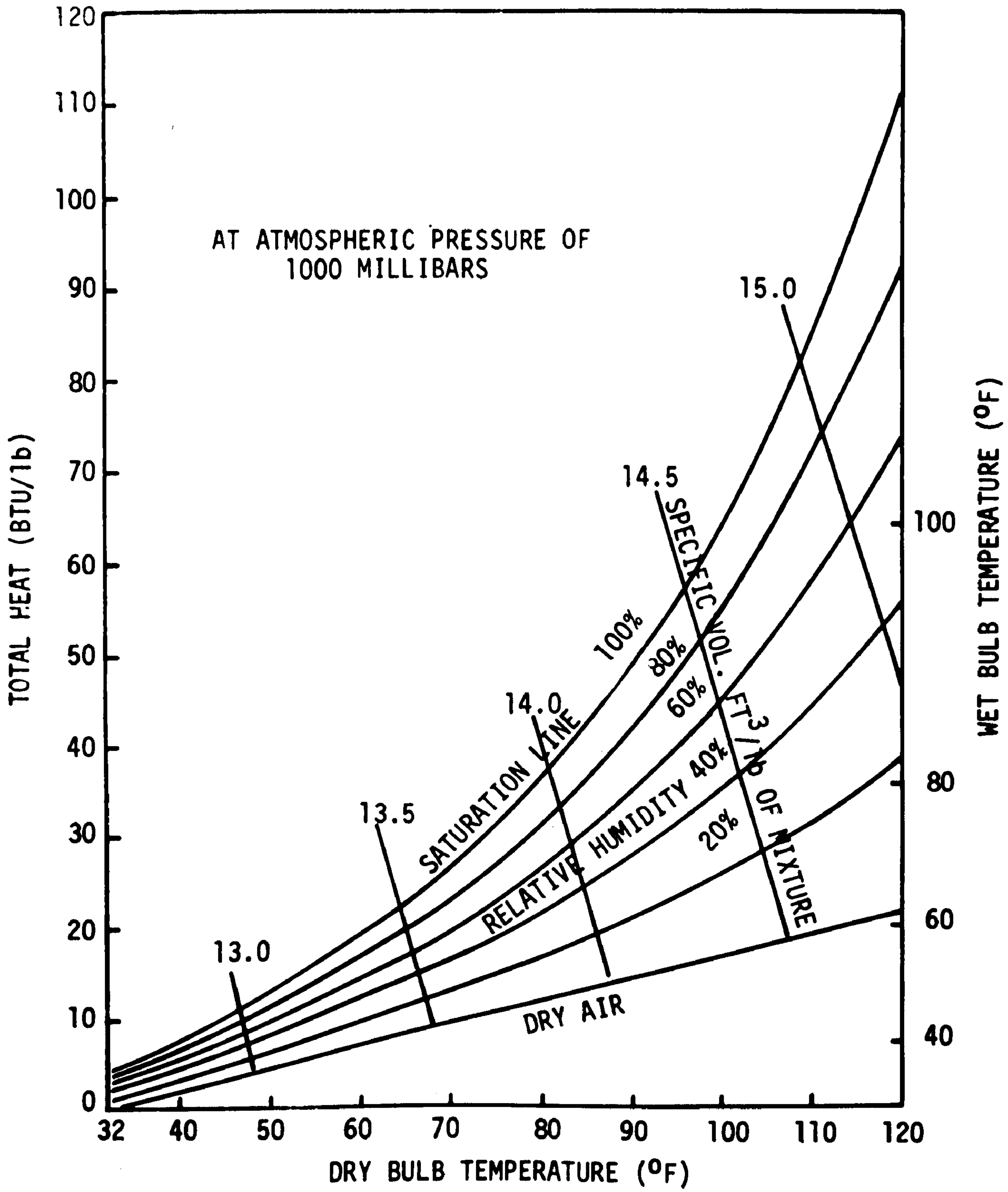

FIG. 3 TEMPERATURE - TOTAL HEAT PSYCHROMETRIC CHART

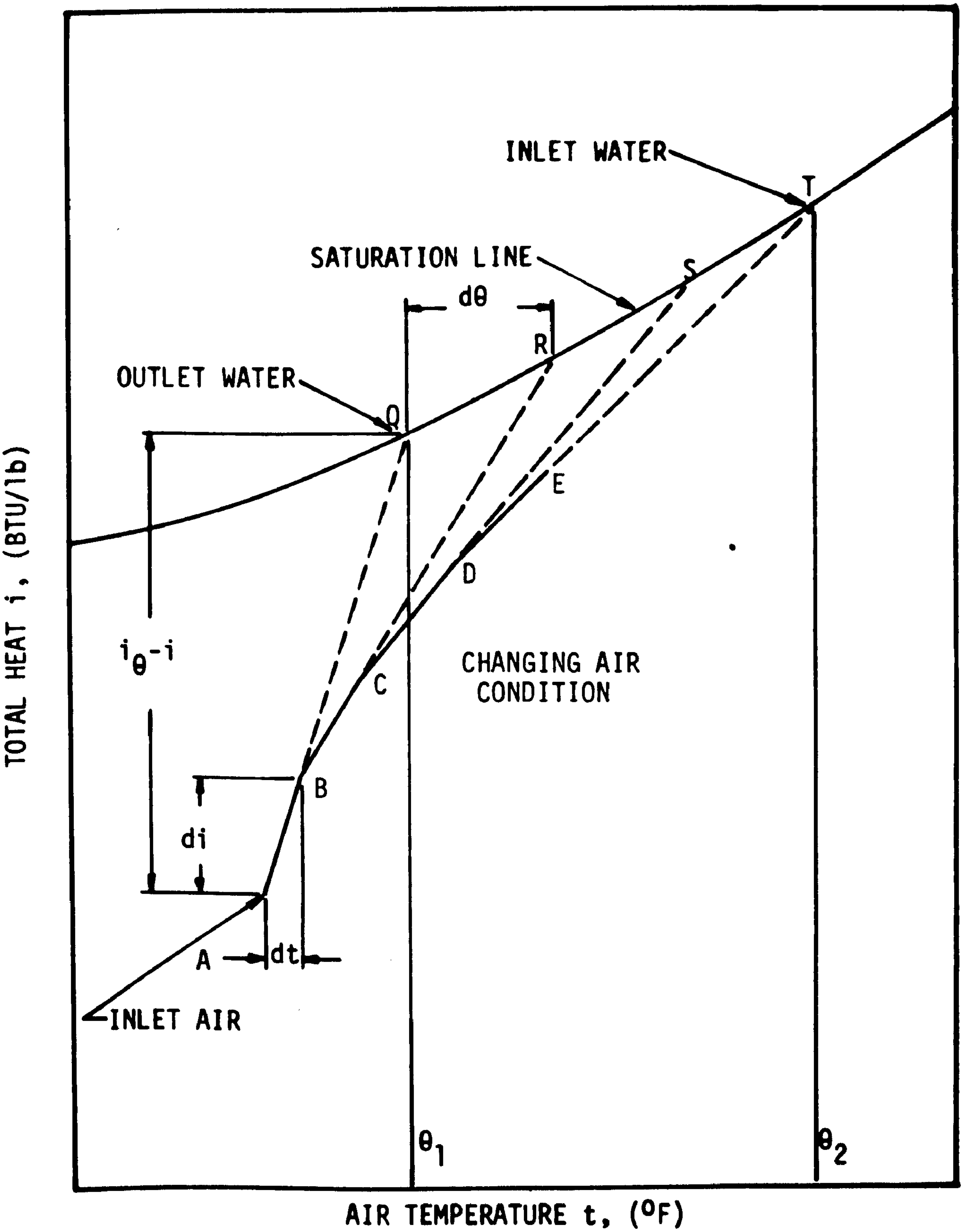

FIG. 4 CHANGING AIR CONDITION

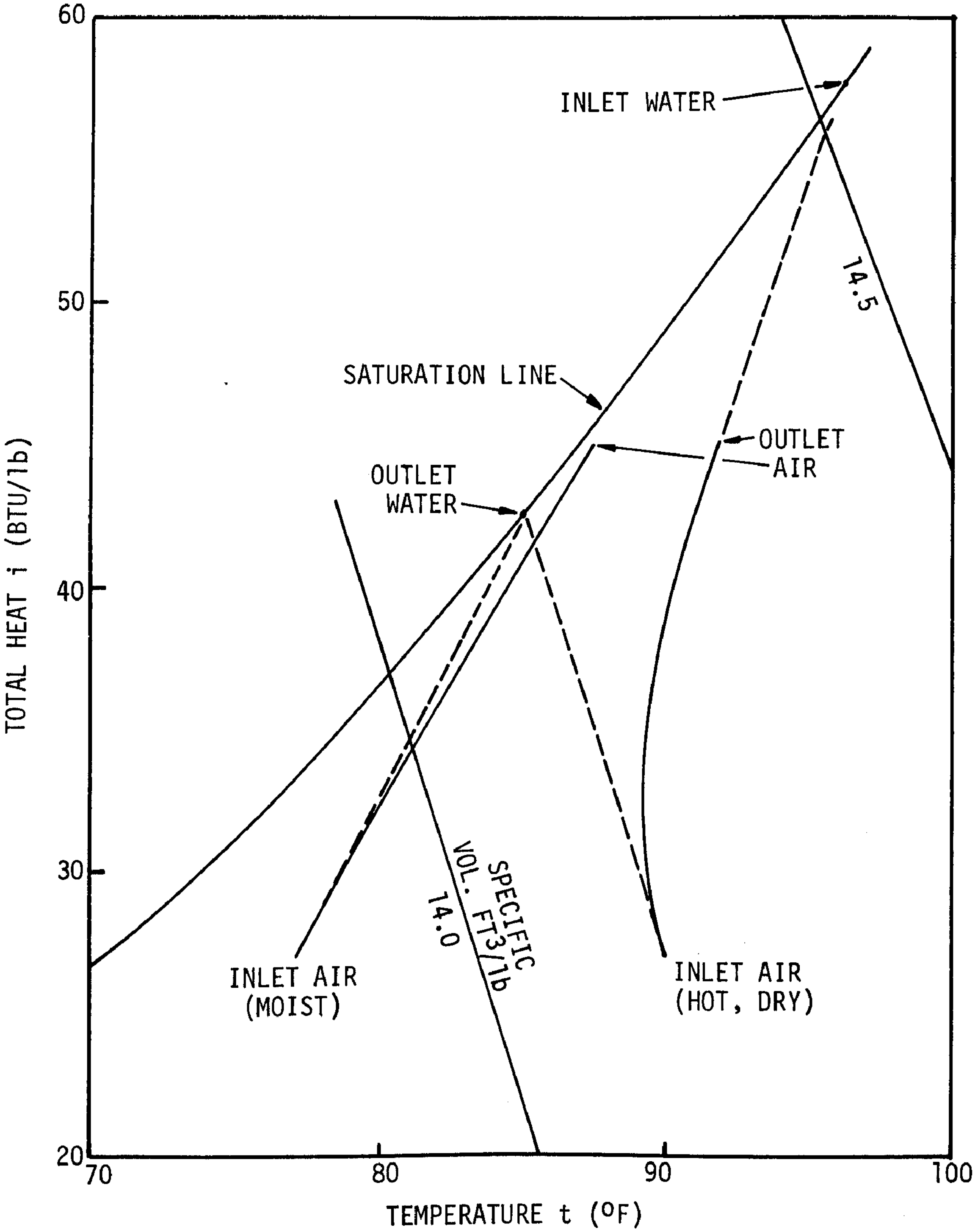

FIG. 5 TWO EXAMPLES OF CHANGING AIR CONDITIONS

air is striving to reach the state of the saturated air with which it is locally in contact across the packing. Initially, the inlet air (point A) "sees" the saturated air across the bottom element of packing surface at the outlet water temperature (point Q), thus, the state of the air will try to reach point Q by traveling along the path AQ. After a small exchange of energy has taken place, the air has reached state B and has moved along the packing to a point where it is in contact with the saturated air at a different water temperature (point R). The state of the moist air then begins to change by moving along the path BR. Continuation of this process yields the locus of states of the air flowing through the packing as a kind of "pursuit" curve (line A-B-C-D-E).

Figure 5 shows pursuit curves for two different atmospheric conditions, one cool and moist (the curve on the left), the other hot and dry (the curve on the right). The difficulty in using a natural draft cooling tower in hot dry climates is illustrated by the pursuit curve on the right. If the atmospheric condition were hotter and dryer (further to the right) the inlet air would "aim" toward the outlet water at a shallow angle, initially, and the state of the air would tend to cross the lines of constant specific volume in the wrong direction. Under such conditions, the air density would increase, and it would be difficult to get the tower "started." Towers constructed in hot-dry climates often require somewhat larger chimney heights to provide the necessary draft, since the density differences between the incoming and exiting air are so small. Additionally, increasing the inlet water temperature will promote a higher cooling efficiency.

SECTION III

MATHEMATICAL MODEL

Simplified Derivations

The total heat approximation for heat and mass transfer, developed by Merkel around 1925 (see Reference 4), states that the energy transferred equals the energy lost by water which must equal the change in the total heat of the air (i.e., the gain in energy of the air). Using this approximation, and neglecting the small changes in water and air flow rates due to evaporation:

$$\frac{h_G}{C_p} (i_\theta - i)\, dA \simeq L\, C_{PL}\, d\theta \simeq G\, di \quad . . . . (1)$$

where,

h_G = Convection coefficient of heat transfer for air, BTU/hr ft² °F

C_p = Specific heat of the air vapor mixture, BTU/lb °F

$\frac{h_G}{C_p}$ = Coefficient of mass transfer, lb/hr ft²

θ = Water temperature, °F

i_θ = The total heat of saturated air and water vapor at θ, BTU/lb

i = Total heat of the air at the air temperature, BTU/lb

dA = Increment of heat transfer surface area, ft²/ft² of cross-section

L = Water flow rate per ft² of cross-section, lb/hr ft²

C_{PL} = Specific heat of water, ≈ 1 BTU/lb °F

$d\theta$ = Differential change in the temperature of the water as it flows over the surface dA, °F

G = Airflow rate per ft^2 of cross-section, lb/hr ft^2

di = Differential change in the total heat of the air as it passes over dA, BTU/lb.

Therefore,

$$d\theta = \frac{(i_\theta - i)}{L\ C_{PL}} \frac{h_G}{C_p} dA \qquad (2)$$

$$di = \frac{(i_\theta - i)}{G} \frac{h_G}{C_p} dA \qquad (3)$$

Also, the change in air temperature due to sensible heating equals the sensible heat transferred from the water to the air:

$$G\ C_p\ dt = h_G\ (\theta - t)\ dA \qquad (4)$$

where,

t = Air temperature, °F

dt = Differential change in the temperature of the air as it flows over the surface dA, °F.

Therefore,

$$dt = \frac{(\theta - t)}{G} \frac{h_G}{C_p} dA \qquad (5)$$

Counterflow

Film flow packing in a counterflow tower is shown schematically in Figure 6. Starting at the bottom of the packing with values for θ,

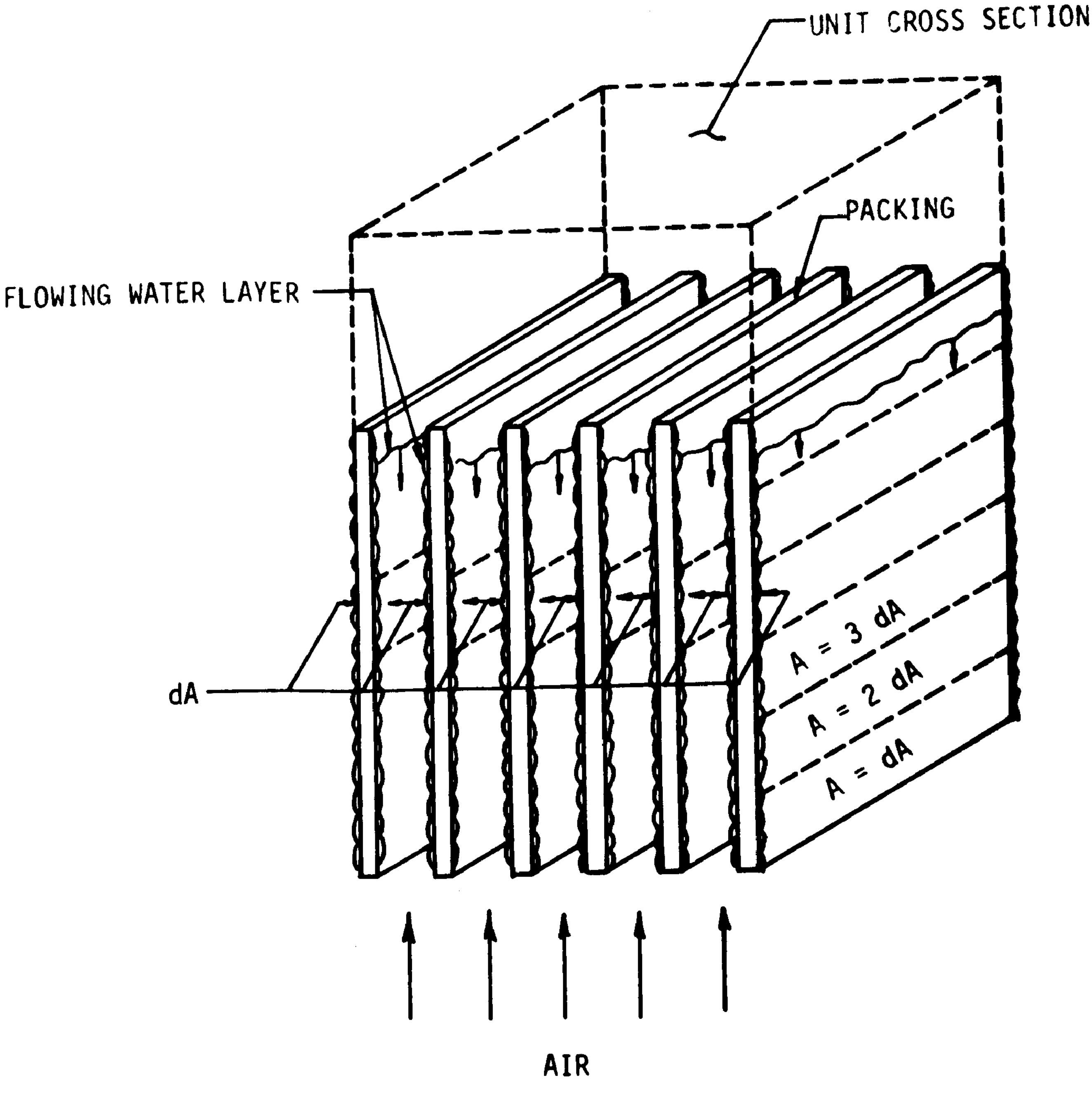

FIG. 6 COUNTERFLOW SCHEMATIC

i, and t equal to outlet water temperature, and inlet air total heat and temperature, respectively, Equations 2, 3, and 5 are used to calculate the changes in these quantities, i.e., $d\theta$, di, and dt, as the air and water flow across the differential packing areas (dA) The design magnitude of the water flow rate (L) and estimates for the air flow rate (G) and heat transfer coefficient (h_G) are also required for the computations. New values for water temperature (θ), air total heat (i), and air temperature (t) are obtained by stepwise integration until the top of the packing is reached:

$$\theta_{A + dA} = \theta_A + d\theta \quad (6)$$

$$t_{A + dA} = t_A + dt \quad (7)$$

$$i_{A + dA} = i_A + di \quad (8)$$

where the subscript A identifies the element of packing surface area where the differential changes are evaluated and A + dA represents the next element of surface, as shown in Figure 6. When A + dA equals the total area available, the integration is complete and the inlet water temperature and the condition of the exit air are presented for the initial conditions. Since outlet water temperature is usually desired, it must be assumed initially and adjusted by trial and error until the given inlet water temperature results. This is done within the computer program, which also adjusts the airflow rate so that it corresponds to the quantity determined by the friction loss, air density and tower height. A simplified flow chart of the computer program which outlines the logic is given in Figure 7. A complete description of the program is presented in Appendix III.

The method of integration used here is similar to the arithmetic method developed by Wood and Betts and illustrated graphically in Figure 4. If dt in Figure 4 were calculated for each step by Equation 5, the method becomes essentially the same integration procedure that is presented in this paper. One advantage in using dA instead of dt as the variable of integration is that it is easier to evaluate the performance of a given tower. Another advantage is that it is possible to extend the method to crossflow towers.

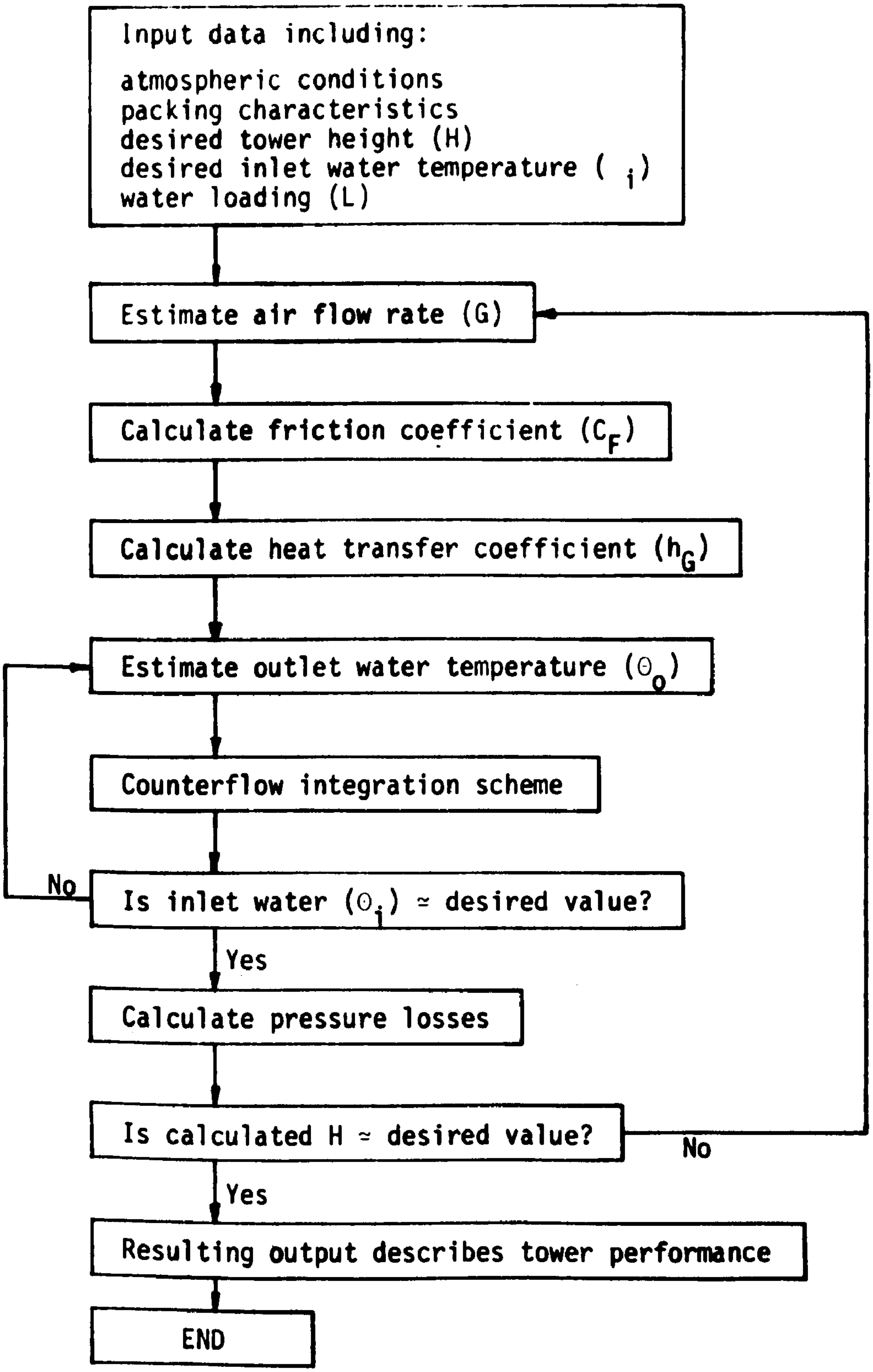

FIGURE 7. SIMPLIFIED FLOWCHART OF COUNTERFLOW COMPUTER SYSTEM

Crossflow

As shown schematically in Figure 8, the crossflow packing is divided up into rows and columns designated by the indices I and J, with water flowing down the columns and air flowing across the rows. (Parallel plate packing is used in this schematic for illustrative purposes, not to indicate an actual crossflow packing arrangement. Although the authors do not know of a crossflow tower using parallel plate packing, such an arrangement may be practical.) The rows and columns delineate rectangular elements of surface area $dA_{I,J}$.

By using the appropriate subscripts denoting rows and columns, one can rewrite Equations 2, 3, and 5 to describe the differential changes in water temperature (θ), air total heat (i), and air temperature (t) within crossflow packing:

$$d\theta = \frac{(i_{\theta_{I,J}} - i_{I,J})}{L_J \, C_{PL}} \left(\frac{h_G}{C_p}\right) dA_{I,J} \quad (9)$$

$$di = \frac{(i_{\theta_{I,J}} - i_{I,J})}{G_I} \left(\frac{h_G}{C_p}\right) dA_{I,J} \quad (10)$$

$$dt = \frac{(\theta_{I,J} - t_{I,J})}{G_I} \left(\frac{h_G}{C_p}\right) dA_{I,J} \quad (11)$$

The integration scheme is similar to the one used for the counterflow case, except the differential changes in water temperature apply down a column and the differential changes in air temperature and air total heat apply along a row:

$$\theta_{I+1,J} = \theta_{I,J} - d\theta \quad (12)$$

$$i_{I,J+1} = i_{I,J} + di \quad (13)$$

$$t_{I,J+1} = t_{I,J} + dt \quad (14)$$

Water temperature for all elements of the top row are equal to the inlet water temperature, and air temperature and total heat for all elements of the first column are equal to that of the incoming air.

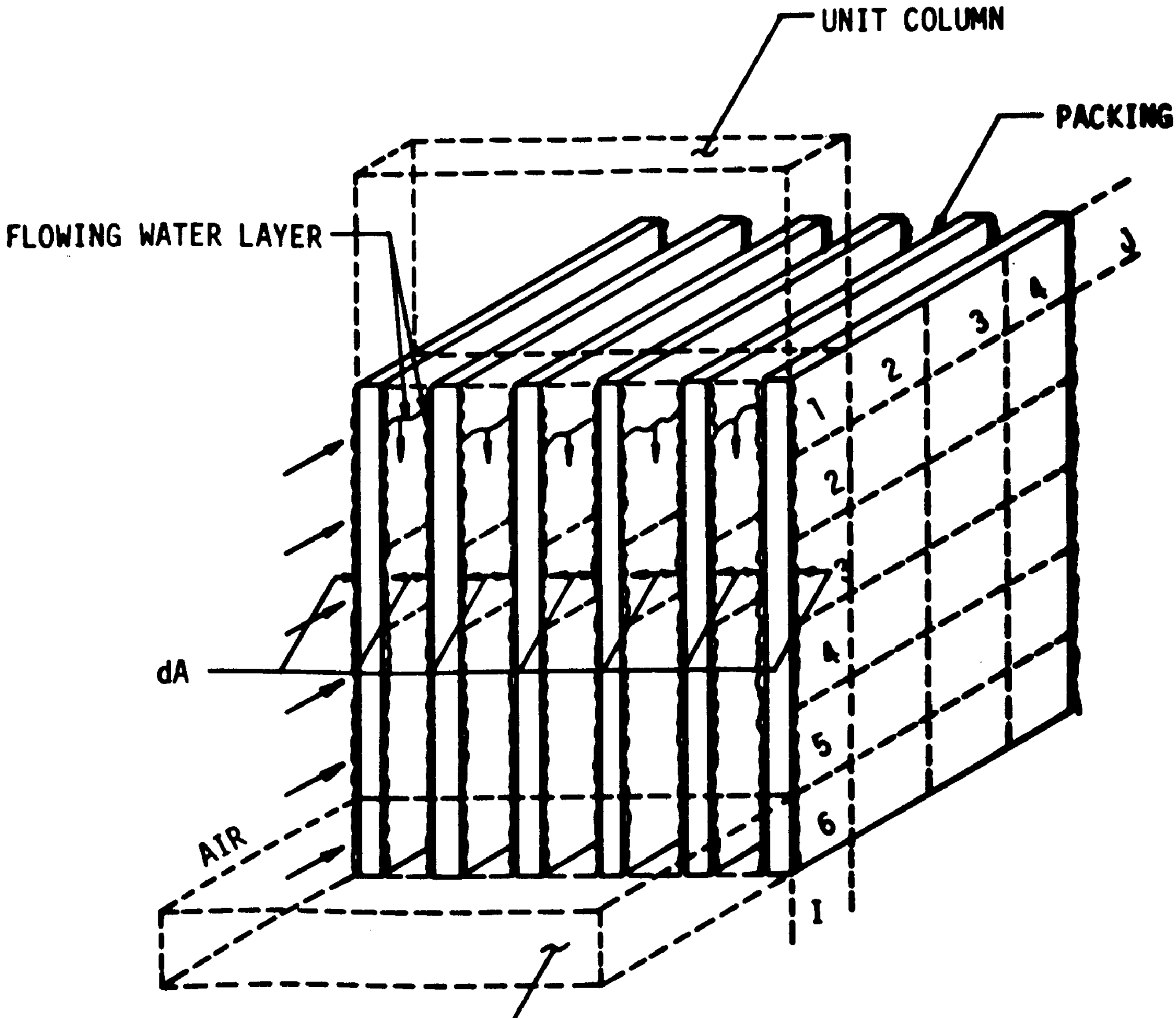

FIG. 8 CROSSFLOW SCHEMATIC

Starting with the element (1,1), one solves for water temperature in each successive area element of the first column as the water flows down until the outlet water temperature for that column is evaluated. The water temperature in the next column is evaluated in a similar manner starting with the inlet water temperature at the top of the column. However, the air that the water contacts in each of the elements of this column is changed, since the air has passed across the first column of water. The new magnitudes of air temperature and total heat computed for each row are used in the integration as the water flows down the column. This process is continued until the final column has been evaluated. In this way it is possible to compute a temperature distribution throughout the packing grid. A mixed outlet water temperature is then calculated for the water flow out of all the columns, and mixed air temperature and total heat are similarly computed for the outlet air

A flow chart for the crossflow method is shown in Figure 9. In the crossflow calculations it is not necessary initially to estimate the outlet water temperature, since it can be solved for directly. As previously stated, a computer program for crossflow towers is not yet available.

Tower Height

For a natural draft tower, the basic design objective is to achieve a sufficiently high airflow rate. This rate is a function of the difference in pressure across the packing and the friction loss. For a given airflow rate, the driving force acting on the air must equal the friction loss through the tower. A simplified expression for this concept which is used by several investigators (1) is:

$$H \, \Delta\rho = N \frac{\rho V^2}{2g} + \tau L \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \quad (15)$$

where,

H = Tower height, ft

$\Delta\rho$ = Difference in moist air density between the inlet and the top of the packing, lb/ft^3

N = Number of velocity heads lost

ρ = Average moist air density, lb/ft^3

V = Average air velocity, ft/sec

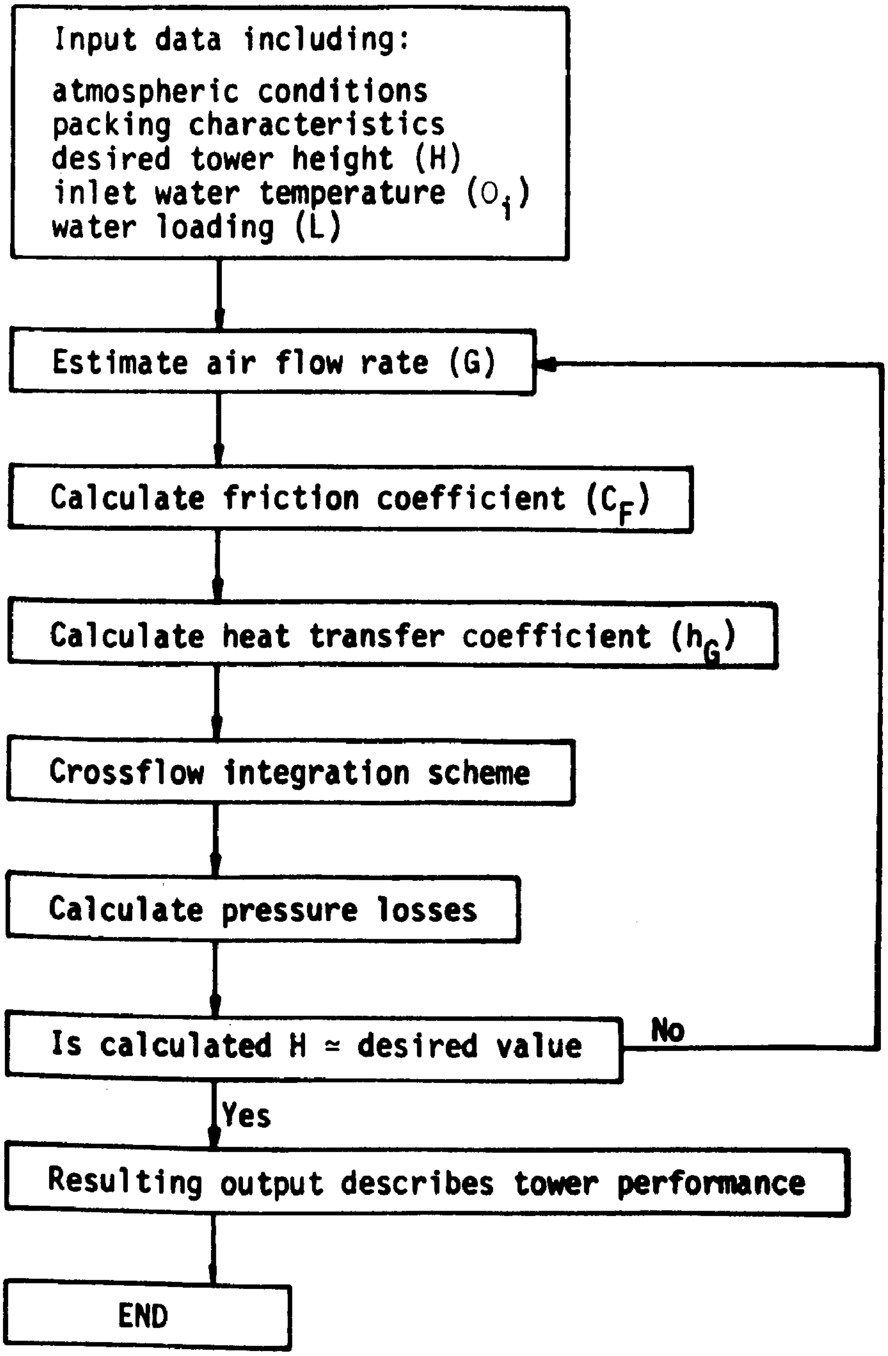

FIGURE 9. SIMPLIFIED FLOWCHART OF CROSSFLOW COMPUTER PROGRAM

g = Acceleration of gravity, ft/sec^2

τ = A friction factor which accounts for the drag of the falling water, hr

In general, as long as a density difference ($\Delta\rho$) exists, a tower height (H) can be selected to obtain the required driving force, however, there is a practical economic limit on tower height.

Some investigators assume that the resistance of the tower to airflow is primarily due to inertia losses caused by the packing and supports, as distinct from friction losses and the drag of falling water. Therefore, in order to simplify their calculations they take the number of velocity heads lost (N) as a constant for a given tower and neglect the friction factor (τ). Actually, the idea that packing resistance is primarily due to inertia losses is somewhat debatable for a film flow packing consisting of parallel plates where skin friction losses predominate. Analytical relationships have been developed which correlate skin friction with heat transfer, and they should apply directly to the simple geometry of parallel plates. Also, expressions for the resistance should realistically include a term due to the shell friction which would involve the shell surface area and hence the height of the tower. In addition, there will be some drag from supports and water distribution pipes, but this can probably be minimized by careful design. In the computer program the resistance is determined by computing the pressure drop at four different sections in the tower (inlet, packing, shell, and obstructions such as drift eliminators) based on the local velocity and configuration through each section.

The direct correlation between skin friction and heat transfer in parallel plate film packing should lead to a more accurate calculation of the heat transfer and friction coefficients. However, the computational technique is not restricted to parallel plate packing. If an effective value of the product h_G A is known or can be determined for other types of packing, effective values for the heat transfer coefficient (h_G) and dA can be determined for use in the computer program.

Estimating Coefficients

The performance of a cooling tower is strongly dependent on the heat and mass transfer, and friction coefficients. Methods of approximating these coefficients are given following

Mass Transfer Coefficient

The mass transfer coefficient K_G, in lb/hr ft^2, based on the difference between the concentration of water vapor in the saturated air in contact with the water and the concentration of water vapor in the main air stream is given approximately by:

$$K_G \simeq \frac{h_G}{C_p} \quad \ldots\ldots (16)$$

Another method used in cooling tower work is to relate K_G directly to the type of packing (3):

$$\frac{K_G a}{L} = \lambda \left(\frac{L}{G}\right)^{-n} \quad \ldots\ldots (17)$$

where,

a = Mean area of water-air interface per cubic foot of packed volume, ft^2/ft^3

λ = Empirical constant, ft^{-1}

n = Empirical constant.

Values of n and λ for different types of packing are given in Reference 3.

Heat Transfer Coefficient

Two methods are used to estimate the heat transfer coefficient. These are the methods presented by Rish (5) and the heat transfer relations based on a modified Reynolds analogy.

Rish's Method - Rish presents a semi-empirical equation developed for plate type packing which, rearranged, yields:

$$h_G = \frac{C_p\, C_f\, G}{2 + 7.16\, C_f \left(\frac{L}{G}\right)^{-0.25}} \quad \ldots\ldots (18)$$

where,

C_f = Friction coefficient.

Standard Heat Transfer Correlation - A common heat transfer relationship used in tube, duct and annulus work is the modified form of the Reynolds analogy (2). In the Reynolds analogy, heat and momentum are assumed to be transferred by analogous processes in turbulent flow. For Reynolds numbers from 10,000 to 120,000 and Prandtl numbers in the range 0.5 to 100, the Reynolds analogy is modified slightly on the basis of experimental data to yield the following equation:

$$\text{Nusselt No.} = 0.023\ (\text{Reynolds No.})^{0.8}(\text{Prandtl No.})^{0.33}$$

or

$$\frac{h_G D}{k} = 0.023\ \left(\frac{vD\rho}{\mu}\right)^{0.8}\ (Pr)^{0.33} \quad \ldots\ldots\ldots\ldots (19)$$

where,

D = Hydraulic diameter, ft (the hydraulic diameter is 4 times the flow cross-section divided by wetted perimeter, thus for an annulus or large, closely spaced plates, the hydraulic diameter is 2 times the distance between the annulus walls, or 2 times the distance between the plates)

v = Air velocity, ft/hr (for a water film having appreciable velocity, v should be the relative velocity between the air and the water)

k = Conductivity of the moist air, BTU/hr ft °F

μ = Coefficient of viscosity, lb/hr ft.

The Prandtl number is defined as the ratio of the kinematic viscosity (a measure of the rate of momentum transfer between molecules) to the thermal diffusivity (a measure of the ratio of the heat transmission to the energy storage capacity of the molecules). The Prandtl number for air varies with temperature around 0.7.

Friction Coefficient

Two methods are used to estimate the friction coefficients.

Rish's Method - For flat asbestos-cement sheets, 1-inch on centers, under counterflow conditions, Rish (5) gives the following expression:

$$C_f = 0.0192\ (\frac{L}{G})^{0.5} \quad (20)$$

Standard Friction Correlation - For Reynolds numbers from 10,000 to 120,000 C_f is given by the empirical relation:

$$C_f = 0.046\ (\text{Reynolds no.})^{-0.2} \quad (21)$$

Presently, the counterflow program can use either Rish's expressions to calculate heat transfer and friction coefficients for parallel plate packing or it can use Equation 17 and Lowe and Christie's data (3) for other types of packing. The program can be readily modified to use other relations for computing the coefficients for different types of packing.

Estimating Pressure Loss

The total pressure drop in a tower is due to the cumulative effect of form drag, skin friction of the packing, and an effective pressure loss due to the contraction of the incoming air.

Form Drag

The drag force, in lb, is given by:

$$\text{Drag} = C_D\ A_D\ \frac{\rho V^2}{2g} \quad (22)$$

where,

C_D = Drag coefficient for obstructions based on the dimension or drag area (A_D).

This is converted to the pressure drop by dividing by the appropriate area, A_{ref}, of the airflow over which this force acts. Therefore, pressure drop due to form drag, ΔP_f (lb/ft²) is:

$$\Delta P_f = C_D\ \frac{A_D}{A_{ref}}\ \frac{\rho V^2}{2g} \quad (23)$$

Skin Friction

The formula for the pressure loss due to skin friction of the packing, ΔP_s (lb/ft^2), is similar to that for form drag:

$$\Delta P_s = C_f \frac{A}{A_{ref}} \frac{\rho V^2}{2g} \quad (24)$$

The quantities $C_D \frac{A_D}{A_{ref}}$ or $C_f \frac{A}{A_{ref}}$ are often referred to as N, the number of velocity heads lost.

Contraction Loss

In addition to the pressure drop due to the packing or obstructions, there may also be a pressure drop to the contraction of the air stream within the tower. When this air stream does not expand to fill the tower, Lowe and Christie (3) show that N for this loss can be estimated by:

$$N_{contraction} = 0.167 \left(\frac{d}{b}\right)^2 \quad (25)$$

where,

d = Tower diameter at the lower edge of the shell, ft

b = Height of the air opening, ft

Spray Loss

Rish (5) indicates that the pressure drop in velocity heads due to water falling from a sheet of packing may be estimated by:

$$N_{spray} = 0.16\, b \left(\frac{L}{G}\right)^{1.32} \quad (26)$$

SECTION IV

EXAMPLE COMPUTATIONS

To "test" the program, a set of example computations were performed using the counterflow model.

Initially, the program was tested to determine the proper number of integration steps. By setting a fixed value for the product h_GA, it was possible to compare the results computed by the program using various numbers of integration steps with results obtained from the "Integral" solution presented in a paper by Wood and Betts (6). The following data are given by Wood and Betts (6):

$$h_GA/L\ C_p = 0.816\ ft^2$$

Outlet water temp. = 85°F

Air dry-bulb temp. = 90°F

Relative humidity = 37%

C_p = 0.24 BTU/lb °F

L = 1200 lb/ft² hr

G = 800 lb/ft² hr

Therefore, the magnitude of h_GA is computed as:

$$h_GA = (0.816\ ft^2)\ (L\ C_p)$$

$$h_GA = (0.816\ ft^2)\ (1200\ lb/ft^2\ hr)\ (0.24\ BTU/lb\ °F)$$

$$h_GA = 235\ BTU/hr\ °F$$

The area required can be evaluated by dividing h_GA by an assumed value for h_G. For example, if an h_G of one BTU/hr ft² °F is assumed, then A = 235 ft² per unit of cross-section. Therefore, for 10 integration steps, dA = 235/10 = 23.5; 20 integration steps, dA = 235/20 = 11.75; 100 integration steps, dA = 235/100 = 2.35; etc.

Parallel plate packing constructed of 1/4-inch thick asbestos cement sheets spaced 1-inch on centers provides a total of 24-square feet of wetted surface in each cubic foot of packing.

Therefore, the total packing height can be calculated as:

$$\text{Packing height} = \frac{(235 \text{ ft}^2)}{(24 \text{ ft}^2/\text{ft})}$$

$$\text{Packing height} = 9.8 \text{ ft}$$

Thus, for 10 integration steps, the program will calculate changes in air and water parameters at 0.98 foot vertical intervals; for 20 integration steps, 0.49 foot intervals; etc.

Table 1 gives the results obtained with various numbers of integration steps. Wood and Betts results are shown for comparison. This table shows that a large number of integration steps are not necessary for reasonable results. Computations with cooler, moister air show the same effect. In applying the program to various situations, it was found that 20 integration steps are reasonable, both in terms of accuracy and computer time.

The first test checked only that portion of the program dealing with heat and mass transfer (Equations 2, 3, 5, 6, 7, and 8). To test the total program, the Wood and Betts data were used with two sets of air conditions. Rish's expressions for heat transfer and friction coefficients, Equations 18 and 20, respectively, were employed. Inlet pressure losses (i.e., form drag) were neglected. A counterflow tower with a diameter of 300 feet and an air inlet height of 20 feet were assumed.

Skin friction losses in the packing were computed using Equation 24, where for the stated packing size and spacing, $A/A_{ref} = \frac{235}{.75} = 314$.

This ratio refers to the area for surface friction divided by the amount of open space in a one square foot horizontal section of packing. For this case, the packing itself takes up 1/4-inch of every inch, so 75 percent of the space is vacant.

Table 2 gives the results of the computer runs for two sets of air conditions. A tower height of 350 ± 10 ft. and an inlet water temperature of 97 ± 0.1°F were assumed.

Comparing the results in Table 2 with those in Table 1 is not advisable, since Table 2 gives answers based on different values of the heat transfer coefficient (h_G) and air flow rate (G). The most significant difference between the results for the two inlet air conditions is the effect on cooling range. It is easily seen that the air at 77°F and 70 percent relative humidity gave

TABLE 1

EFFECT OF CHANGING INTEGRATION INTERVALS

No. of Integration Steps	10	20	100	200	Wood & Betts
dA, ft^2	23.5	11.75	2.35	1.18	--
Vertical intervals, ft	0.98	0.49	0.10	0.05	--
Inlet θ, °F	96.88	96.86	96.85	96.85	97
Outlet t, °F	91.21	91.36	91.49	91.50	91.6
Outlet i, BTU/lb	44.57	44.55	44.54	44.53	44.6
Outlet relative humidity, %	83.93	83.33	82.87	82.82	83.5

TABLE 2

COUNTERFLOW EXAMPLE

Item	Air at 90°F - 37% Rel. Hum.	Air at 77°F - 70% Rel. Hum.
Inlet water temperature (°F)	97.0	97.0
Outlet water temperature (°F)	85.5	82.8
Cooling range (°F)	11.5	14.2
Outlet air temperature (°F)	92.6	88.3
Outlet air total heat (BTU/lb)	48.9	45.6
Outlet relative humidity (%)	91.4	98.0
Heat transfer coefficient, h_G (BTU/hr ft^2 °F)	1.088	1.363
Friction coefficient, C_f	0.02691	0.02236
Air Flow (lb/hr ft^2)	611	885
Tower height (ft)	353	353

better cooling than the air at 90°F and 37 percent relative humidity, i.e., a cooling range of 14.2 °F versus a cooling range of 11.5 °F.

The effect of different values of inlet water temperature and heat transfer coefficient (h_G) can be noted by comparing the intermediate results of the computer runs. Figures 10 and 11 show the combined effect of various values for inlet water temperature, h_G, and tower height on tower performance for hot, dry air and cool, moist air, respectively. The vertical lines illustrate the cooling range for a given tower height, as shown on the abscissa, for the inlet water temperature indicated by the location of the top of the line. The heat transfer coefficient, h_G, corresponding to the conditions in the tower is given at the top of each line. The towers characterized in Table 2 are tower A (Figure 10) and tower G (Figure 11). All of the other towers represented are theoretically feasible, but were rejected by the program because their height was not within 10 feet of 350 feet as prescribed.

Note the significance of operating a tower with a higher inlet water temperature, particularly under hot-dry conditions, Figure 10. The cooling range can be increased without significantly increasing the outlet water temperature, e.g., for towers C and D compare the difference between inlet water temperatures to the difference between outlet water temperatures. A similar comparison can be made for towers H and I, Figure 11. The cooling range might also be increased by increasing the tower height, but the height required may be uneconomical, e.g., tower F. The fact that the moist temperate condition is more favorable can be seen by comparing the two plots and in particular, towers A and G.

The performance of a typical counterflow natural draft tower 400 feet high is shown in Figure 12. Note that the tower performance (i.e., its cooling range) falls off more rapidly with increasing relative humidity at high air temperatures.

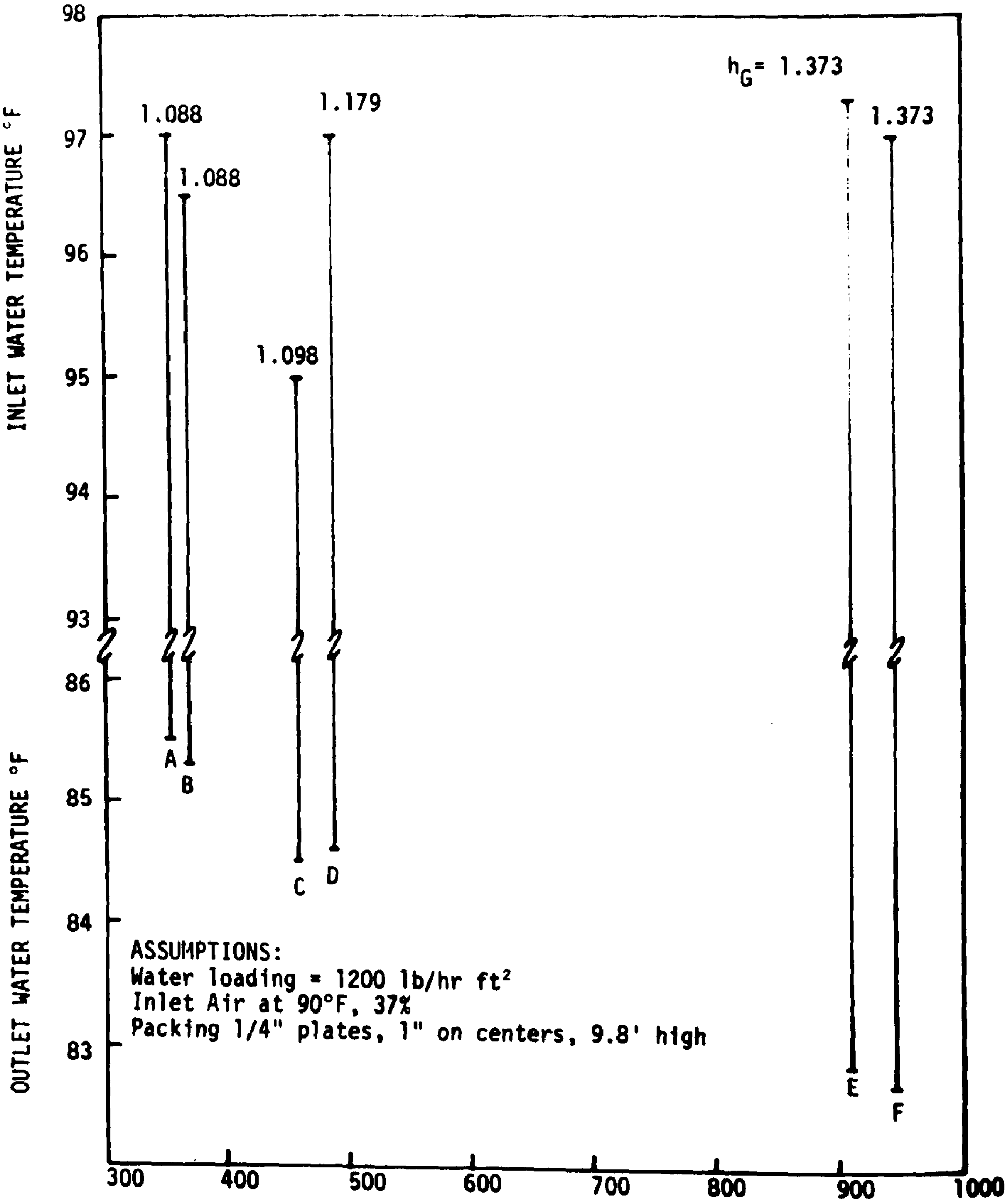

FIGURE 10: PERFORMANCE OF TOWERS - HOT, DRY CONDITIONS

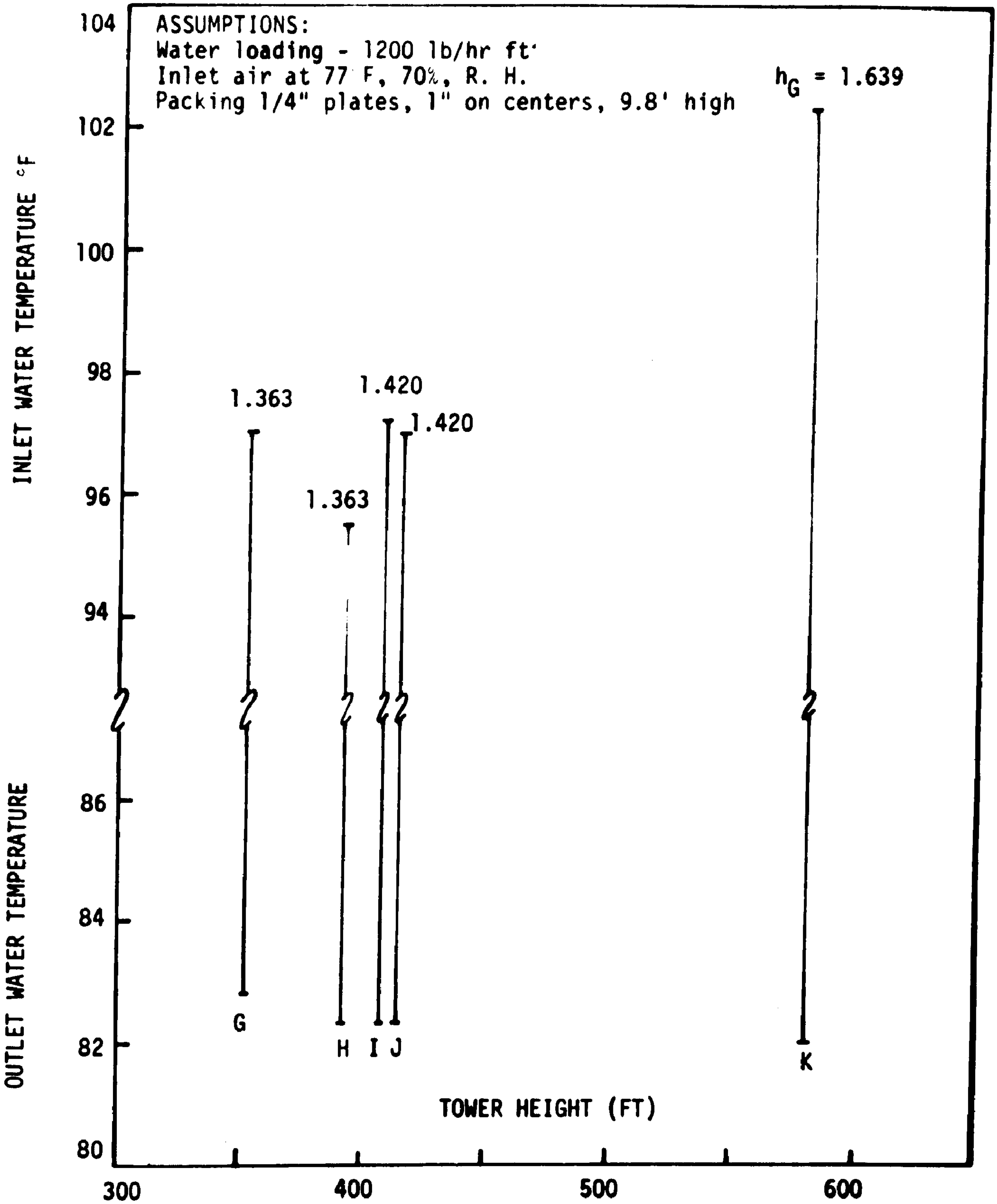

FIGURE 11: PERFORMANCE OF TOWERS - MOIST CONDITIONS

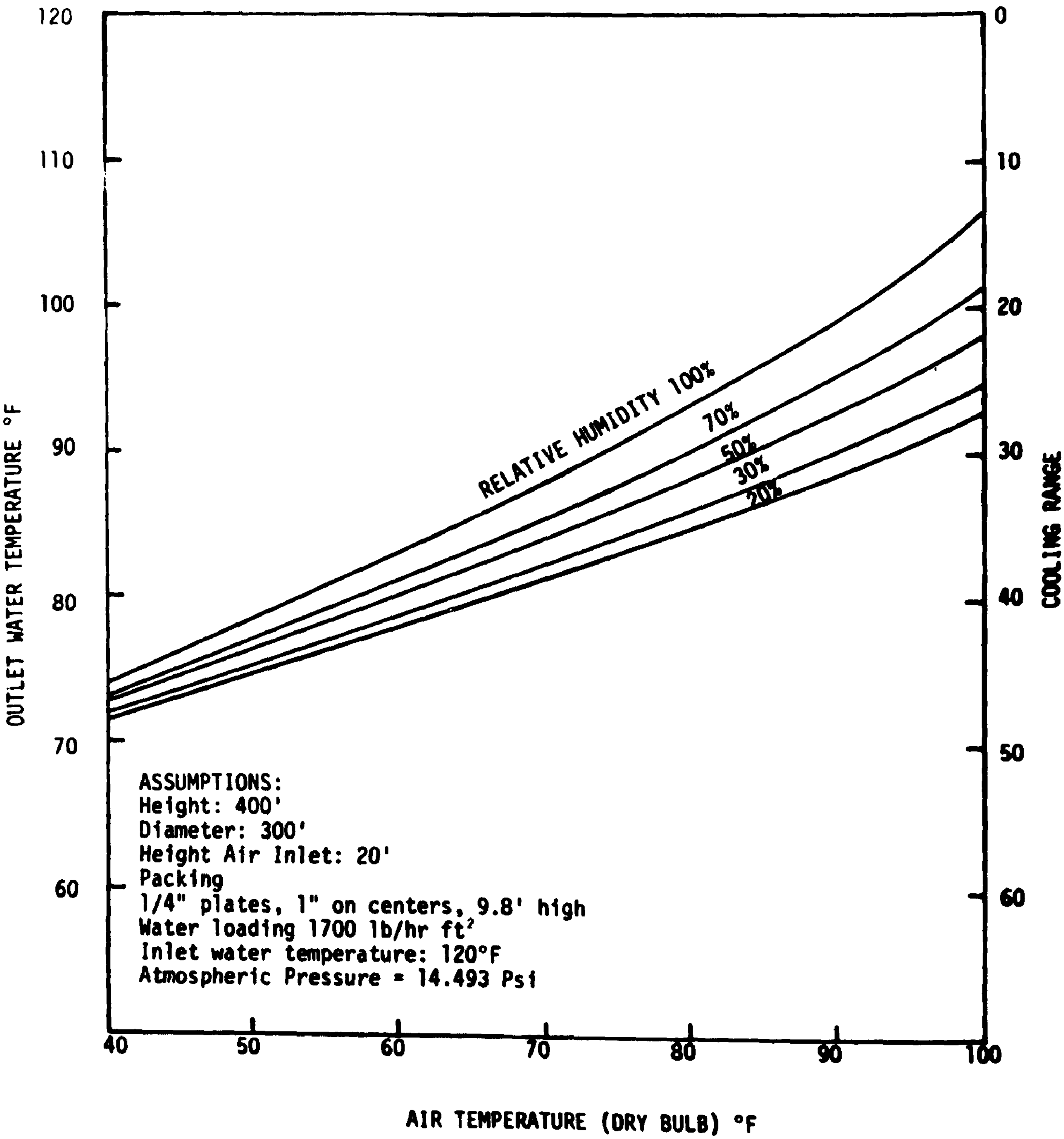

FIGURE 12: PERFORMANCE OF A TYPICAL TOWER

REFERENCES

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3. Lowe, H. J., and Christie, D. G., "Heat Transfer and Pressure Drop Data on Cooling Tower Packings and Model Studies of the Resistance of Natural Draft Towers to Airflow," International Heat Transfer Conference, Denver, 1962, pp. 933-950.

4. McKelvey, K. K. and Brooke, M., The Industrial Cooling Tower, Elsevier Company, Amsterdam, 1958.

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SYMBOLS

The following symbols are used in this paper:

A = Area of contact surface at the air-water interface, ft^2/ft^2 of cross-section

A_c = Cross-sectional area, ft^2

A_D = Drag area, ft^2 (See Equation 22)

A_{ref} = Reference area for computing pressure drop, ft^2

a = Mean area of water-air interface per cubic foot of packed volume, ft^2/ft^3

b = Height of the air entrance at the tower base, ft

C_D = Drag coefficient

C_f = Skin friction coefficient

C_p = Specific heat of the air, BTU/lb °F

C_{PL} = Specific heat of the water, BTU/lb °F

D = Hydraulic diameter, ft

d = Tower diameter, ft

G = Airflow rate per square foot of cross-section, lb/hr ft^2

g = Acceleration of gravity, ft/sec^2

H = Tower height, ft

h_G = Heat transfer coefficient, BTU/hr °F ft^2

I = Index coordinate for unit row in crossflow case

i = Total heat of moist air, BTU/lb

i_θ = Total heat of saturated air at temperature θ, BTU/lb

J = Index coordinate for unit column in crossflow case

K_G = Mass transfer coefficient, lb/hr ft^2 (See Equation 16)

k = Thermal conductivity, BTU/hr ft °F

L = Water flow rate per square foot of cross-section, lb/hr ft^2

N = Number of velocity heads lost

n = Empirical constant (See Equation 17)

t = Air temperature, dry-bulb, °F

V = Velocity of the air, ft/sec

v = Air velocity, ft/hr

θ = Water temperature, °F

λ = Empirical constant, ft^{-1} (See Equation 17)

μ = Coefficient of viscosity, lb/hr ft

ρ = Density of the moist air, lb/ft^3

τ = Friction factor to account for the drag of falling water, hr (See Equation 15)

ΔP_f = Pressure drop due to form drag, lb/ft^2

ΔP_s = Pressure drop due to skin friction, lb/ft^2

APPENDIX - COMPUTER PROGRAM

The main body of the paper dealt with the basic integration scheme, along with the pressure loss, and heat and mass transfer relations. This appendix deals primarily with the details of the computer program.

The program was developed on the Control Data 3300 computer at Oregon State University, and then modified to operate on FWPCA's IBM System/360 computer facility. All references herein are to the System 360 version of the program, which is written in Fortran IV and compiled on the G level compiler.

RUNNING THE PROGRAM

Input Options and Variables

The program is written so that only those variables which have significance for the case being run need be input.

Demonstration Case

If the user wishes to run the program without any input variables, the program may be called with no cards in the input stream. The program then assumes a test case, and runs with preassigned values. Output options of printing the initial assumptions, and of printing the results of iterations, are assumed. A sample output is shown later in this appendix.

Required Variables

If the user does not want a test case, he must input tower geometry (HTOWER, DTOWER, and HAIRIN), a local meteorology (AIRTI and HUM) and inlet water parameters (WTRTI and WTRF or WTRFT). If some, but not all of those are input, the program will terminate after listing the input variables.

Parallel Plate Packing

Default values - If no packing related variables are input, the program assumes parallel plate packing of 1/4-inch plates on 1-inch centers, 9.8 feet high.

Other sizes - The user may alternatively input THICK, SPACE, and HPACK. The pressure loss in the packing is then computed:

$$\Delta P = \frac{C_f \rho A_{drag} V^2}{2g}$$

with

$$V = \frac{G}{A_{flow} \rho}$$

These formulae, however, make certain assumptions with which the user may not agree. They are:

$$A_{flow} = \frac{\text{SPACE-THICK}}{\text{SPACE}} ,$$

$$A_{total} = \frac{24 \times \text{HPACK}}{\text{SPACE}} ,$$

$$A_{drag} = \frac{A_{total}}{A_{flow}}$$

The values of ATOTAL, AFPK, and ADPK may be input in lieu of SPACE, etc., to access the program beyond the above assumptions.

In any case, when using parallel plate packing, the program computes C_f and h_G from the empirical formula of Rish (5), equations 20 and 18.

Other Packings

The program allows for use of the experimental data of Lowe and Christie (3) for different types of packing. There are two possibilities:

1. If LAMBDA, N, ADPK, AFPK, and HPACK are input, the program computes h_G with Lowe and Christie's data (equation 17), but C_f to be used in the packing pressure loss equation is computed from Rish (equation 20).

2. If LAMBDA, N, HPACK, P13, P23, P16, and P26 are input, the packing pressure loss is interpolated from the velocity head experimental data of Lowe and Christie.

Pressure Loss Due to Tower Structure and Geometry

If the user wishes to include form drag in the pressure loss computations, he has the option of inserting the variables, AFIN, ADIN, CDIN to compute inlet pressure losses; AFOT, ADOT, and CDOT to compute outlet losses; and AFSL, ADSL, and CDSL to compute losses due to the shell.

The program uses the variables AF-- to compute the velocity using airflow and density. It then applies this velocity to equation 23 using AD-- and CD-- to compute a pressure loss with a simple "form drag" scheme. If a more sophisticated method, such as accounting for several rows of structural columns, is desired, AF--, AD--, and CD-- may be adjusted to achieve the desired results without reprogramming.

Input Variables

Variable Name	Default Value*	Units	Meaning
ADIN	0.	ft^2/ft^2	Normalized cross-sectional drag area at the air inlet.
ADOT	0.	ft^2/ft^2	Normalized cross-sectional drag area at the air outlet.
ADPK	314.	ft^2/ft^2	Surface area per unit flow through area to be used with C_f in computing pressure loss in packing due to skin friction coefficient.
ADSL	0.	ft^2/ft^2	Normalized cross-sectional drag area in the shell.
AFIN	1.	ft^2/ft^2	Normalized cross-sectional flow through area at the air inlet.
AFPK	.75	ft^2/ft^2	Portion of tower cross-section which is unobstructed by packing.
AFOT	1.	ft^2/ft^2	Normalized cross-sectional flow through area at the outlet of the packing.
AFSL	1.	ft^2/ft^2	Normalized cross-sectional flow through area in the shell.
AIRF	WTRF	lbs/hr ft^2	An initial guess for the normalized air flow rate. The program modifies this as execution proceeds.

* A default value is the value assumed by the computer if the variable has not been input. If the user inputs a variable, it will be used in place of the default value.

Variable Name	Default Value	Units	Meaning
AIRTI	90	°F	Inlet air temperature, dry bulb.
ATMOS	14.493	lb/in^2	Atmospheric pressure.
ATOTAL	235.	ft^2	Total packing surface area in one square foot of tower cross-section.
CDIN	0.		Drag coefficient for the inlet structures.
CDOT	0.		Drag coefficient for the outlet structures.
CDSL	0.		Drag coefficient for the shell.
CP	.24	BTU/lb °F	Specific heat of moist air.
DTOWER	300	ft	Tower diameter at packing.
HAIRIN	30	ft	Height of the air inlet.
HPACK	9.8	ft	Height of the packing.
HTOWER	350	ft	Tower height.
HUM	.37		Relative humidity of the inlet air.
LAMBDA	None		Lowe & Christie's empirical λ(See equation 17 and Table 3).
N	None		Lowe & Christie's empirical N (See equation 17 and Table 3).
P13	None	vel/hds/ft	Lowe & Christie's pressure drop data (See Table 3).

Variable Name	Default Value	Units	Meaning
P16	None	vel.hds/ft	Lowe & Christie's pressure drop data (See Table 3).
P23	None	vel.hds/ft	Lowe & Christie's pressure drop data (See Table 3).
P26	None	vel.hds/ft	Lowe & Christie's pressure drop data (See Table 3).
SPACE	1.	inches	Center to center spacing of parallel plates.
STEPS	20		Number of integration steps.
THICK	.25	inches	Thickness of a single parallel packing plate.
TOLERH	10.	ft	If the computed tower height is within ±TOLERH of the specified value, the program ends.
TOLERT	.1	°F	If the computed inlet water temperature is within ±TOLERT of the specified value, the program accepts the computation.
WTRF	1200	$lbs/hr\ ft^2$	Normalized water flow rate.
WTRFT	8.5×10^7	lbs/hr	Total water flow rate through tower.
WTRTI	97	°F	Inlet water temperature.
WTRTO	WTRTI - 25	°F	An initial guess for the outlet water temperature.

PACKING DATA - TABLE 3*

Lowe & Christie Packing No.	Description of Packing	Figure No.	Dimensions in Fig. 13: h_a (inches)	v_a (inches)	H (inches)	W (inches)	S (inches)	Transfer: λ	n	Pressure Drop (vely. heads/ft), Water 1000 lb/hr ft², AIR: P13 3 ft/sec	P16 6 ft/sec	Water 2000 lb/hr ft², AIR: P23 3 ft/sec	P26 6 ft/sec
7	Triangular Splash Bar	13 (a)			6	9	3	0.09	0.50	2.7	2.0	3.5	2.6
8	"	"			6	6	3	0.094	0.50	3.7	3.3	4.8	3.9
9	"	"			6	5 & 13 Alternately	3	0.096	0.45	2.0	1.7	2.6	2.1
10	"	"			6	12	3	0.075	0.42	1.7	1.3	2.4	1.7
11	"	"			4½	18	2¼	0.072	0.47	1.9	1.6	2.8	2.1
14	Flat Asbestos Sheets	13 (c)			1¾			0.088	0.70	0.7	0.55	1.0	0.7
15	"	"			1½			0.11	0.72	0.8	0.6	1.1	0.8
16	"	"			1¼			0.12	0.76	0.9	0.7	1.1	0.9
17	"	"			1			0.14	0.73	0.9	0.7	1.2	1.0
19	Triangular Splash Bar	AS 13 (a)	With Bars Upside Down		6	9	3	0.084	0.49	3.4	2.7	5.1	3.6
21	Corrugated Asbestos Sheets	13 (d)	2⅛	5¾	1¾			0.21	0.69	3.2	2.7	3.8	3.1
22	"	"	2⅛	5¾	1¼			0.22	0.61	4.3	3.1	5.1	3.6
23	"	"	2⅛	5¾	2¼			0.18	0.68	3.1	2.7	3.5	3.1
24	"	13 (e)	h_b=2⅛	v_b=5¾	1¾			0.11	0.66	1.0	0.5	1.6	0.8
25	"	13 (f)	2⅛	5¾	1			0.17	0.58	4.4	4.1	5.1	4.8
26	Triangular Splash Bar	13 (b)			4	8	0	0.074	0.52	1.2	0.9	2.0	1.3
27	"	"			4	8	2	0.087	0.55	1.2	0.9	2.1	1.3
28	"	"			4	10	2	0.079	0.58	0.9	0.75	1.7	1.2
29	"	"			4	10	0	0.072	0.54	0.9	0.7	1.6	1.1
30	"	"			4	7½	2	0.095	0.53	1.3	0.9	2.2	1.3
31	"	"			4	6	2	0.098	0.54	1.7	1.3	2.6	1.8
32	"	"			5	8	2½	0.093	0.46	1.3	0.8	2.0	1.3
37	"	"			2	6	1	0.187	0.65	4.8	4.1	6.4	5.4

*Taken from Reference 3

TABLE 3 (CONT.)

Lowe & Christie Packing No.	Description of Packing	Figure No.	Dimensions in Fig. 13: h_a (inches)	v_a (inches)	H (inches)	W (inches)	S (inches)	Transfer: λ	n	Pressure Drop (vely. heads/ft), 1000 lb/hr ft² AIR: P13 3 ft/sec	P16 6 ft/sec	2000 lb/hr ft² AIR: P23 3 ft/sec	P26 6 ft/sec
38	Asbestos Louvres	13 (g)	1	5 3/4	1	10 3/4		0.203	0.70	2.7	2.5	3.1	3.0
39	"	13"	1	5 3/4	1	6 3/4		0.287	0.68	4.8	4.2	5.8	4.9
40	"	"	1	5 3/4	1	20 3/4		0.118	0.69	1.7	1.5	2.1	1.8
41	"	"	1	5 3/4	1	15 3/4		0.154	0.67	2.1	1.8	2.6	2.2
42	Triangular Splash Bar	13 (b)			5	7 1/2	2 1/2	0.095	0.49	1.3	0.8	2.3	1.4
43	"	"			6	7 1/2	3	0.089	0.47	1.2	0.7	2.2	1.2
45	Asbestos Louvres	13 (g)	1 1/2	5 1/4	1	6 1/4		0.351	0.66	10.5	9.5	12.0	10.5
47	"	13 (g)	1 1/2	5 1/4	1 1/2	6 1/4		0.247	0.66	6.8	6.1	8.4	7.2
48	"	"	1 1/2	5 1/4	1 1/2	15 1/4		0.169	0.65	4.7	4.0	5.5	4.7
49	"	"	1 1/2	5 1/4	1 1/2	20 1/4		0.101	0.63	2.9	2.3	3.6	2.6
50	Rectangular Splash Bar	13 (h)			8	9	2	0.086	0.52	2.5	1.9	3.1	2.7
51	"	"			8	12	2	0.08	0.53	1.7	1.4	2.5	1.8
			Corrugations Horiz. h_a	v_a	Corrugations Vert. h_b	v_b							
55	Corrugated Asbestos Sheets	13 (i)	2 1/8	5 3/4	2 1/8	5 3/4		0.186	0.73	3.8	3.3	4.4	3.8
57	"	"	1 1/16	2 7/8	1 1/16	2 7/8		0.308	0.80	9.0	8.0	9.0	9.0
58	"	"	1 1/16	2 7/8	2 1/8	5 3/4		0.207	0.79	3.2	2.8	3.9	3.2
59	"	"	2 1/8	5 3/4	1 1/16	2 7/8		0.248	0.79	10.8	10.0	11.5	11.0
61	"	"	2 3/8	7	2 3/8	7		0.163	0.71	4.3	3.8	5.4	4.3
62	"	"	1 1/16	2 7/8	8 3/4	2 15/16		0.133	0.72	2.4	1.6	3.1	2.1

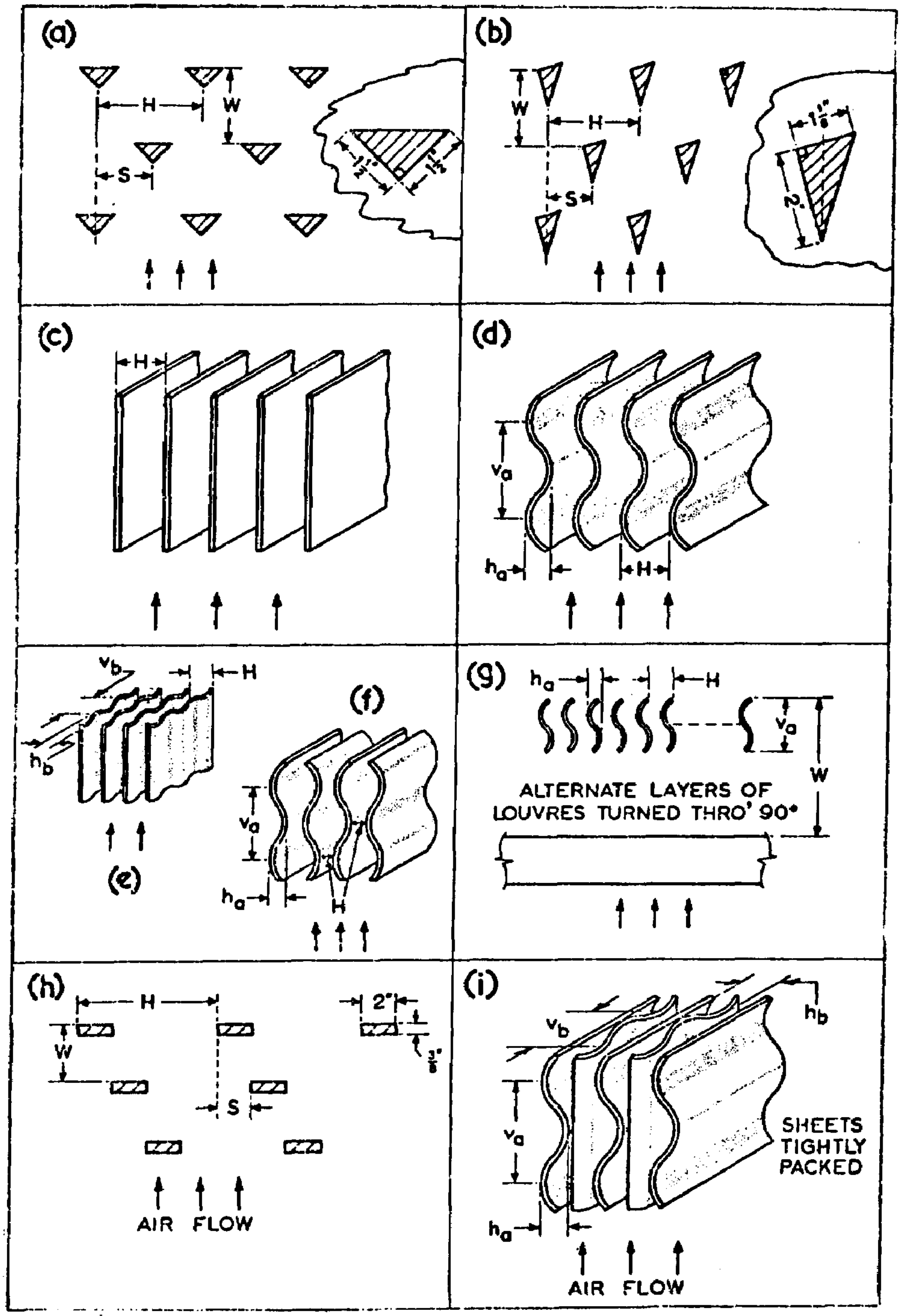


FIGURE 13: TYPES OF PACKING (from Lowe and Christie (3))

Output Options

Listing Initial Values

The user has control over whether the initial (input or calculated) values of the variables will be listed.

Listing Results of Iterations

Results of each iteration are listed after an adjustment to WTRTO or AIRF is made. A message is also written whenever the program makes an iteration to modify either of the above.

Listing Results of each Integration Step

Information about the status of the integration may be printed after each step. This is essentially a diagnostic mode, since it generates voluminous output. As used here, each iteration encompasses one or more integrations. Thus, each time a line of iterative data is printed, STEPS lines of integration step results would be printed.

Listing Format

Column Title	Units	Meaning
ITER NO		Iteration number.
WATER LOSS	lb/hr ft^2	Water evaporated per square foot of tower cross-section.
OUTLET AIR DENSITY	lb/ft^3	Density of the air above the packing.
AIR VELOCITY IN PACKING	ft/sec	Air velocity in packing (equals nominal velocity if Lowe & Christie's data are used).
CALC HEAT TRANS COEFF	BTU/hr $ft^{2}{}^{\circ}F$	Calculated heat transfer coefficient (0 if Lowe & Christie's data are used)

Column Title	Units	Meaning
TOWER CHARACTERISTIC (K*A/L)		Tower characteristic or number of transfer units.
SKIN FRICTION COEFF		Skin friction coefficient (0 if Lowe & Christie's data are used).
RELATIVE HUMID	(decimal fraction)	Relative humidity.
INLET WATER TEMP	°F	Inlet water temperature.
OUTLET AIR TEMP	°F	Air temperature above the packing.
OUTLET AIR ENTHALPY	BTU/lb	Air enthalpy above the packing.
PROFILE PRESSURE LOSS	lb/ft^2	Sum of the pressure losses at the inlet, outlet and shell.
PACKING PRESSURE LOSS	lb/ft^2	Pressure loss due to packing.
SPRAY PRESSURE LOSS	lb/ft^2	Pressure loss due to water falling from the bottom of the packing.
VENA CON PRESSURE LOSS	lb/ft^2	Pressure loss due to the Vena-Contracta.
SHELL PRESSURE LOSS	lb/ft^2	Pressure loss due to the shell.
TOWER HEIGHT	ft	Total tower height.

Card Deck Set-ups

The program described herein is stored as a load module on a disk pack at U. S. Time Sharing, Inc., to which most FWPCA System/360 terminals have access. To invoke the program, use the following JCL and data cards:

```
       <job card>
//JOBLIB DD DSN=KENBYRAM, DISP=(OLD,KEEP),UNIT=2314
// VOL=(PRIVATE, RETAIN, SER=FWPCH)
//STEP1 EXEC PGM=COOLTOWR, REGION=200K
//FT06F001    DD  SYSOUT=A,DCB=(RECFM=FBSA,LRECL=133,BLKSIZE=1330)
//FT05F001    DD *
       <program data cards>

/*
```

<program data cards> consists of

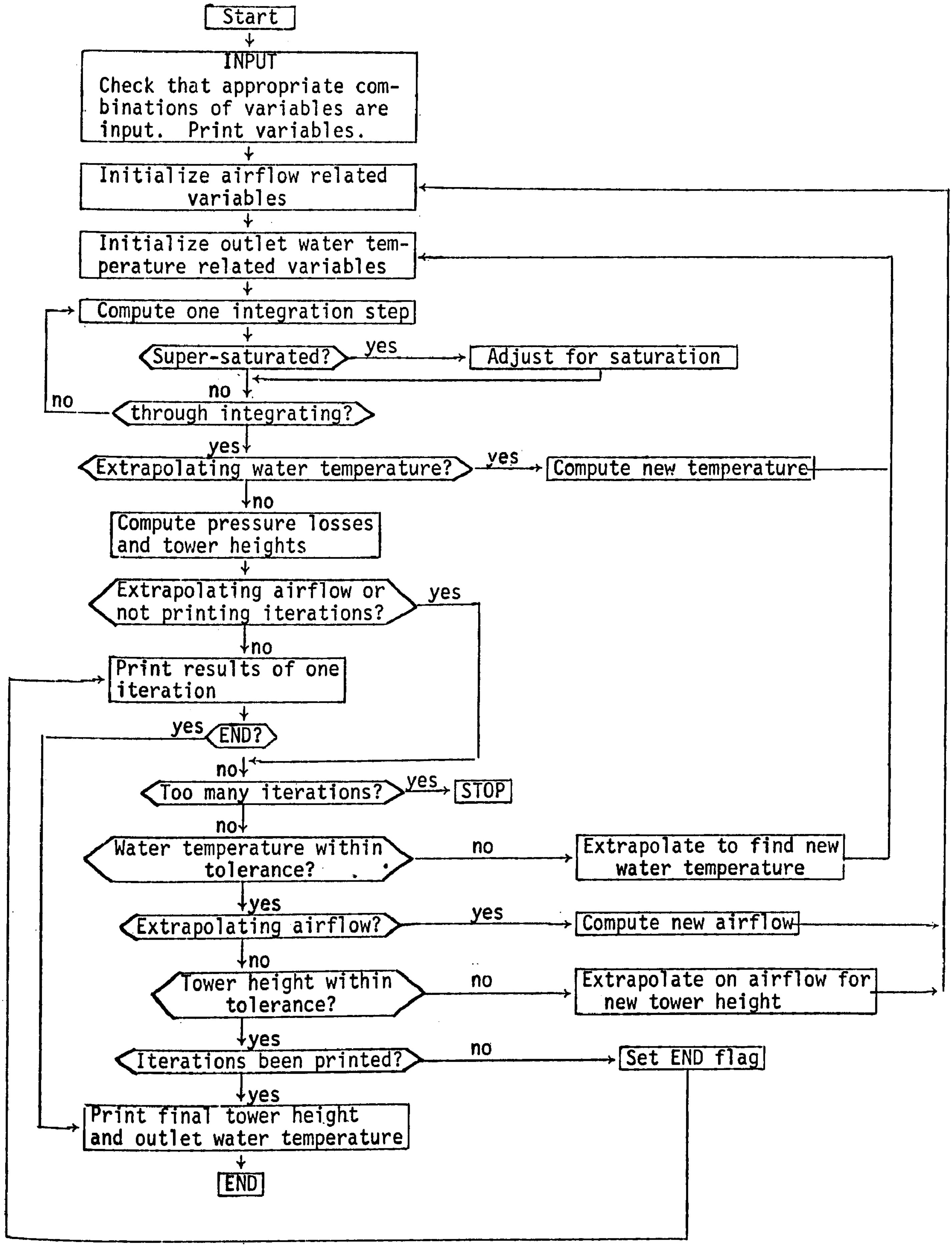
1. An "output options" card, with a "T" in
   column 1 if results of iterations,
   column 2 if all steps of each integration,
   column 3 if input variables and assumptions,
   are to be printed. Columns are blank otherwise.

2. Any number of "input variable cards" with
   columns 1-8: variable name, left justified, and spelled correctly.
   columns 9-18: variable value, anywhere in field, with decimal point punched.

One variable fits on each card, with the cards in any order. Not all variables need be input (see page 49).

To run the demonstration case, <program data cards> are omitted.

BLOCK FLOW CHART



EXPLANATION OF PROGRAM VARIABLES

Variable Name	Definition
A	The area integrated over as the integration proceeds.
AIRFL	The last air flow rate used by the program.
AIRT	The air temperature as the integration proceeds.
C	A temporary variable.
CF	Friction coefficient.
CONWTR	The weight of water which has been condensed out as the integration proceeds.
DA	A portion of the total area, = ATOTAL/STEPS.
DAIRT	The change in air temperature during one integration step.
DENT	The change in enthalpy of the air during one integration step.
DNSARI	Density of the inlet air.
DNSARO	Density of the outlet air.
DNSAVG	Average of the outlet and inlet air densities.
DTODTI	The rate of outlet water temperature change versus inlet water temperature change.
DWTRT	The change in water temperature during one integration step.
ENDFLG	Logical: true, if the program has reached a normal termination.
ENT	The air enthalpy as the integration proceeds.
ENTI	The enthalpy of the inlet air.
ENTSA	The enthalpy of the air during the saturation adjustment loop.

Variable Name	Definition
ENTSAT	The enthalpy of a pound of saturated air-water mixture.
EXTAFL	Logical: true, if this iteration is being made to extrapolate airflow.
EXTWTO	Logical: true, if an iteration is being made to extrapolate outlet water temperature.
FND	A variable which is either "*" or blank, indicating whether an initial value has been read in, or assumed, respectively.
H	Calculated tower height.
H1	Holds the last calculated value of tower height while a new value is being extrapolated.
H2	Holds the calculated value of tower height. H1 and H2 are then used in an extrapolation for airflow.
HENT	The adjusted enthalpy of the air-water droplet mixture as its temperature is raised in the saturation adjustment loop.
HG	Heat transfer coefficient.
HUMI	The relative humidity of the air as the integration proceeds.
INHIB	Logical: true, if program execution is to be terminated before starting the iterations (if input data are in error, for example).
IPG	Counts the pages printed out.
JD	Integer value of day of month.
JM	Integer value of month.
JULDAT	The subroutine which fetches month, day and year from the operating system.
JY	Integer value of last two digits of year.
LBW	Pounds of water (droplets) per pound of air at any point in the packing, according to the status of the integration.

Variable Name	Definition
LBVI	Pounds of vapor per pound of air, in the inlet air.
LBVLBA	Pounds of vapor per pound of air at any point in the packing, according to the integration.
LBVLBS	Pounds of vapor per pound of air at saturation.
LITER	Counts the lines printed on a page with results of iterations, and controls heading printing.
LSTEP	Counts the lines printed on a page with the step by step results of iterations and controls heading printing.
NB	Controls which of the packing related initial variables will be printed. The first 26 values of VALS() are printed, and then the NBth through NEth values are printed.
NE	See above.
NOITER	The number of iterations, or the number of times the program has completed an integration.
P1	Temporary variable.
P2	Temporary variable.
PPP	Logical: true, if the tower has parallel plate packing.
PRIN	Logical: true, if Lowe & Christie's pressure loss constants have been input (P13, P16, P23, P26).
PRINP	Logical: true, if the input data and initial assumptions are to be printed.
PRITER	Logical: true, if the results of each iteration are to be printed.

Variable Name	Definition
PRLIN	Pressure loss at the inlet.
PRLPK	Pressure loss in the packing.
PRLPR	Pressure loss due to profile (=PRLIN+PRLOT).
PRLOT	Pressure loss at the outlet.
PRLSL	Pressure loss in the shell.
PRLSP	Pressure loss due to spray.
PRSTEP	Logical: true, if each step in the integration is to be printed.
PSA	Saturation vapor pressure at the air temperature.
PSAH	Saturation vapor pressure in the loop which adjusts super-saturated air to saturated air at constant enthalpy.
PSAT()	Function which obtains the saturation vapor pressure from a temperature used as the function argument. It is looked up in a table.
PSW	Saturation vapor pressure at the water temperature.
READIN()	Logical: true, if a particular initial variable has appeared in the input stream. Example: If READIN(2)=TRUE, AIRTI has been input, AIRTI≡VALS(2)=value, VNAMES(2)='AIRTI.'
T	Temporary variable used to hold air temperature in the saturation adjustment loop.
T1	Temporary variable.
VV	The value of an input variable, read from the card. It is later placed in VALS().
VALS()	The value of the initial variables, which may be changed by input.

Variable Name	Definition
VHSP	Velocity heads lost to spray interference with airflow.
VHVC	Velocity heads lost due to Vena-Contracta in the tower.
VIN	Air velocity at the inlet.
VN	The input variable name read from the input card, used in searching through the table of VNAMES().
VNAMES()	Alphameric, holds the character representation of the input variable names, for interpreting the input cards.
VNOM	The nominal velocity in the packing, feet/second.
VPEN	The enthalpy of the moisture in the air and used in the saturation adjustment loop.
VPENT	The enthalpy of the vapor in a pound of air.
VPRES	The vapor pressure of the air at any point in the packing.
VPRESI	The vapor pressure of the inlet air.
VPK	Air velocity in the packing.
VOT	Air velocity at the outlet.
VSL	Air velocity in the shell.
WTRLT	The water which condenses out during an integration step.
WTRT1	Holds the last calculated value of inlet water temperature while a new value is being calculated.
WTRT2	Holds the second calculated value of inlet water temperature for extrapolation. WTRT1 and WTRT2 are combined in making an extrapolation.

PROGRAM LISTING

```
      PROGRAM K8
C*********************************************************************
C  PROGRAM FOR PREDICTING NATURAL DRAFT COOLING TOWER PERFORMANCE
C
C  FOR DESCRIPTION, SEE PACIFIC NORTHWEST WATER LABORATORY PAPER
C  NUMBER XX, DATED XX/XX/69
C
C*********************************************************************
      REAL LBVLBA,LBW,LAMBDA,N,LBVLBS,LBVI,KAL
      LOGICAL PRITER,EXTAFL,EXTWTO,PRSTEP,PRINP,READIN,INHIB,ENDFLG,
     *  PPP,PRIN
      DIMENSION READIN(37),VALS(37),VNAMES(37)
      REAL*8 VNAMES,VN
      EQUIVALENCE (WTRTI,VALS(1)),(AIRTI,VALS(2)),(HTOWER,VALS(3)),
     *  (DTOWER,VALS(4)),(HAIRIN,VALS(5)),(HUM,VALS(6)),(WTRFT,VALS(7)),
     *  (WTRF,VALS(8)),(AIRF,VALS(9)),(WTRTO,VALS(10)),
     *  (STEPS,VALS(11)),(TOLERT,VALS(12)),(TOLERH,VALS(13)),
     *  (AFIN,VALS(14)),(AFOT,VALS(15)),(AFSL,VALS(16)),
     *  (ADIN,VALS(17)),(ADOT,VALS(18)),(ADSL,VALS(19)),
     *  (CDIN,VALS(20)),(CDOT,VALS(21)),(CDSL,VALS(22)),
     *  (CP,VALS(23)),(ATMOS,VALS(24)),
     *  (DNSARI,VALS(25)),(THICK,VALS(26)),(SPACE,VALS(27)),
     *  (ATOTAL,VALS(28)),(AFPK,VALS(29)),(ADPK,VALS(30)),
     *  (HPACK,VALS(31)),(LAMBDA,VALS(32)),(N,VALS(33)),
     *  (P13,VALS(34)),(P23,VALS(35)),(P16,VALS(36)),(P26,VALS(37))
      DATA VALS/96.9,90.,357.,300.,33.4,.37,8.5E7,1202.5,2*0.,20.,
     *  .1,10.,3*1.,6*0.,.24,14.493,3*0.,235.,.75,314./
      DATA STAR,BLANK/1H*,1H /,IPG,LITER,LSTEP/0,52,50/,
     *  INHIB,ENDFLG/2*.FALSE./
      DATA VNAMES/5HWTRTI,5HAIRTI,6HHTOWER,6HDTOWER,6HHAIRIN,5HHUM   ,
     *  5HWTRFT,5HWTRF ,5HAIRF ,5HWTRTO,5HSTEPS,6HTOLERT,6HTOLERH,
     *  5HAFIN ,5HAFOT ,5HAFSL ,5HADIN ,5HADOT ,5HADSL ,5HCDIN ,
     *  5HCDOT ,5HCDSL ,5HCP   ,5HATMOS,6HDNSARI,5HTHICK,
     *  5HSPACE,6HATOTAL,5HAFPK ,5HADPK ,5HHPACK,6HLAMBDA,5HN    ,
     *  5HP13  ,5HP23  ,5HP16  ,5HP26  /
C*********************************************************************
C  THE RATHER LONG INPUT SECTION IS DESIGNED TO INSURE THAT
C  APPROPRIATE COMBINATIONS OF VALUES ARE INPUT.  ALL VARIABLES
C  HAVE  DEFAULT VALUE, AND ONLY THOSE WHICH NEED TO BE CHANGED
C  MUST BE INPUT
C*********************************************************************
      WRITE(6,104)
  104 FORMAT(1H1)
      CALL JULDAT(JY,JM,JD)
      DO 70 I=1,37
   70 READIN(I)=.FALSE.
      READ(5,71,END=101)PRITER,PRSTEP,PRINP
      GO TO 77
  101 PRITER=.TRUE.
      PRSTEP=.FALSE.
      PRINP=.TRUE.
      GO TO 87
   71 FORMAT(3L1)
   77 READ(5,72,END=75)VN,VV
   72 FORMAT(A8,F10.0)
      DO 73 I=1,37
```

```
      IF(VN.EQ.VNAMES(I))GO TO 74
   73 CONTINUE
      WRITE(6,76)VN
   76 FORMAT(#0NO VARIABLE NAMED #,A8)
      INHIB=.TRUE.
      GO TO 77
   74 VALS(I)=VV
      READIN(I)=.TRUE.
      GO TO 77
   75 DO 78 I=1,7
      IF(READIN(I))GO TO 81
   78 CONTINUE
   80 WRITE(6,79)
   79 FORMAT(#0NONE OF THE ESSENTIAL INPUT DATA PROVIDED.  THIS#,
     *  # WILL BE RUN AS A TEST CASE#)
      NA=28
      NE=30
      GO TO 84
   81 DO 82 I=1,7
      IF(READIN(I))GO TO 82
      IF(I.EQ.7.AND.READIN(8))GO TO 82
      INHIB=.TRUE.
      WRITE(6,83)VNAMES(I)
   83 FORMAT(#0INPUT VARIABLE #,A8,# IS ESSENTIAL AND WAS NOT READ IN.#)
   82 CONTINUE
   84 ATOWER=DTOWER*DTOWER*.785398
      IF(.NOT.READIN(7))WTRFT=WTRF*ATOWER
      IF(.NOT.READIN(8))WTRF=WTRFT/ATOWER
      IF(.NOT.READIN(10))WTRTO=WTRTI-25.
      IF(.NOT.READIN(9))AIRF=WTRF
      AIRT=AIRTI
      NOITER=0
      VHVC=.167*(DTOWER/HAIRIN)**2
      VPRES=HUM*PSAT(AIRT)
      LBVLBA=.622*VPRES/(ATMOS-VPRES)
      VPENT=1061.+.444*AIRT
      ENTI=CP*(AIRT-32.)+VPENT*LBVLBA
      VPRESI=VPRES
      LBVI=LBVLBA
      DNSAPI=((ATMOS-VPRES)/53.3+VPRES/85.7)*144./(460.+AIRT)
      IF(.NOT.PRINP)GO TO 94
      IPG=IPG+1
      WRITE(6,88)JM,JD,JY,IPG
   88 FORMAT(#1COOLING TOWER PROGRAM  -  LISTING OF INITIAL VARIABLES#,
     *  47X,I2,2(1H/I2),# PAGE#,I3/#0VARIABLE NAME          VALUE#/)
      DO 89 I=1,25
      FND=BLANK
      IF(.NOT.READIN(I))FND=STAR
   89 WRITE(6,90)VNAMES(I),VALS(I),FND
   90 FORMAT(5X,A8,3X,F17.6,1X,A1)
C**********************************************************************
C  DETERMINE PACKING TYPE
C**********************************************************************
   94 PPP=.TRUE.
      PRINP=.FALSE.
      NA=28
```

```
      NE=30
      IF(READIN(28))GO TO 11
      IF(.NOT.READIN(26).AND..NOT.READIN(27))GO TO 3
      IF(READIN(26))GO TO 5
      WRITE(6,83)VNAMES(26)
      INHIB=.TRUE.
    5 IF(READIN(27))GO TO 8
      WRITE(6,83)VNAMES(27)
      STOP
    8 IF(INHIB)STOP
      NB=26
      NE=31
      ATOTAL=24.*HPACK/SPACE
      AFPK=(SPACE-THICK)/SPACE
      ADPK=ATOTAL/AFPK
      GO TO 2
    3 IF(.NOT.READIN(32).AND..NOT.READIN(33))GO TO 2
      PPP=.FALSE.
      ATOTAL=HPACK
      NB=29
      NE=33
      IF(.NOT.READIN(34).AND..NOT.READIN(35).AND..NOT.READIN(36)
     *  .AND..NOT.READIN(37))GO TO 11
      PRIN=.TRUE.
      NB=31
      NE=37
   11 DO 9 I=NB,NE
      IF(READIN(I))GO TO 9
      WRITE(6,83)VNAMES(I)
      INHIB=.TRUE.
    9 CONTINUE
      IF(INHIB)STOP
      WRITE(6,12)
   12 FORMAT(≠0(PARALLEL PLATE PACKING NOT ASSUMED)≠/)
    2 IF(PPP)WRITE(6,13)
   13 FORMAT(≠0(PARALLEL PLATE PACKING ASSUMED)≠/)
      IF(.NOT.PRINP)GO TO 93
      DO 14 I=NB,NE
      END=BLANK
      IF(.NOT.READIN(I))END=STAR
   14 WRITE(6,90)VNAMES(I),VALS(I),END
      WRITE(6,91)
   91 FORMAT(≠0≠,20X,≠*VALUE CALCULATED FROM OTHER INPUT OR ASSUMED≠)
   93 DA=ATOTAL/STEPS
      AIRFL=0.
      IF(INHIB)STOP
C*******************************************************************************
C     END INPUT AND INITIALIZATION
C     START ITERATION
C*******************************************************************************
   95 VNOM=AIRF/(DNSARI*3600.)
      VHSP=.16*HAIRIN*(WTRF/AIRF)**1.32
      IF(PPP)GO TO 16
      KAL=HPACK*LAMBDA*(AIRF/WTRF)**N
      HG=CP*WTRF*KAL/HPACK
      HGOUT=0.
```

```
      IF(.NOT.PRIN)GO TO 16
      T1=VNOM/3.-1.
      P1=(P16-P13)*T1+P13
      P2=(P26-P23)*T1+P23
      VHLPK=((P2-P1)*(WTRF-1000.)/1000.+P1)*HPACK
      CF=0.
      GO TO 15
   16 CF=.0192*(WTRF/AIRF)**.5
      IF(.NOT.PPP)GO TO 15
      HG=CP*AIRF*CF/(2.+CF*71.6*(AIRF/WTRF)**.25)
      KAL=HG*ATOTAL/(CP*WTRF)
      HGOUT=HG
   15 WTRT=WTRTO
      ENT=ENTI
      HUMI=HUM
      A=0.
      LBVLBA=LBVI
      VPRES=VPRESI
      CONWTR=0.
      AIRT=AIRTI
C***********************************************************************
C     INTEGRATION LOOP BEGINS WITH STATEMENT 6
C***********************************************************************
    6 PSW=PSAT(WTRT)
      IF(PSW.EQ.0.)GO TO 110
      ENTSAT=CP*(WTRT-32.)+(1061.+.444*WTRT)*.622*PSW/(ATMOS-PSW)
      C=HG*DA*(ENTSAT-ENT)/CP
      IF(.NOT.PRSTEP.OR.EXTWTO.OR.EXTAFL)GO TO 35
      IF(LSTEP.LT.47)GO TO 36
      IPG=IPG+1
      WRITE(6,37)JM,JD,JY,IPG
   37 FORMAT(*1COOLING TOWER PROGRAM  -  STEP BY STEP RESULTS OF ONE*
     * ,* ITERATION*,38X,I2,2(1H/I2),* PAGE*,I3/
     * *0        WATER    AIR  SATUR  ACTUAL REL PNDS WTR/  VAPOR*/
     * *   AREA    TEMP    TEMP ENTHAL  ENTHAL HUM  PNDS AIR  PRES*/)
      LSTEP=0
      LITER=52
   36 LSTEP=LSTEP+1
      WRITE(6,38)A,WTRT,AIRT,ENTSAT,ENT,HUMI,LBVLBA,VPRES
   38 FORMAT(5F7.1,F6.3,F9.5,F7.4)
   35 DWTRT=C/WTRF
      DENT=C/AIRF
      DAIRT=HG*DA*(WTRT-AIRT)/(AIRF*CP)
      WTRT=WTRT+DWTRT
      ENT=ENT+DENT
      AIRT=AIRT+DAIRT
      A=A+DA
      VPENT=1061.+.444*AIRT
      LBVLBA=(ENT-CP*(AIRT-32.))/VPENT
      PSA=PSAT(AIRT)
      IF(PSA.EQ.0.)GO TO 110
      LBVLBS=.622*PSA/(ATMOS-PSA)
      HUMI=LBVLBA*(.622+LBVLBS)/(LBVLBS*(.622+LBVLBA))
      VPRES=HUMI*PSA
      IF(HUMI.LE.1.)GO TO 99
C***********************************************************************
```

```
C  IF MIXTURE IS SUPER-SATURATED, RAISE TEMPERATURE TO
C  A POINT WHERE MIXTURE IS JUST SATURATED, KEEPING THE TOTAL
C  ENTHALPY CONSTANT
C**********************************************************************
      T=AIRT
   97 T=T+.1
      PSAH=PSAT(T)
      IF(PSAH.EQ.0.)GO TO 110
      VPEN=1061.+.444*T
      LBW=.622*PSAH/(ATMOS-PSAH)
      ENTSA=CP*(T-32.)+VPEN*LBW
      HENT=(LBVLBA-LBW+CONWTR)*(T-32.)+ENTSA
      IF(ENT.GT.HENT)GO TO 97
      CONWTR=LBVLBA-LBW+CONWTR
      ENT=ENTSA
      AIRT=T
   99 IF(A.LT.ATOTAL)GO TO 6
C**********************************************************************
C     END INTEGRATION SECTION
C
C  COMPUTE PRESSURE LOSSES FOR THIS ITERATION
C**********************************************************************
  100 IF(EXTWTO)GO TO 24
      VPENT=1061.+.444*AIRT
      LBVLBA=(ENT-CP*(AIRT-32.))/VPENT
      WTRLT=AIRF*(LBVLBA+CONWTR-LBVI)
      VPRES=LBVLBA*ATMOS/(.622+LBVLBA)
      DNSARO=((ATMOS-VPRES)/53.3+VPRES/85.7)*144./(460.+AIRT)
      DNSARO=DNSARO*(1.+CONWTR)/(1.+CONWTR*DNSARO/62.4)
      DNSAVG=(DNSARI+DNSARO)/2.
      VIN=VNOM/AFIN
      VOT=AIRF/(DNSARO*AFOT*3600.)
      VSL=AIRF/(DNSARO*AFSL*3600.)
      PRLIN=CDIN*DNSARI*.016126*ADIN*VIN**2
      IF(PRIN)GO TO 102
      VPK=AIRF/(DNSAVG*AFPK*3600.)
      PRLPK=CF*DNSAVG*.016126*ADPK*VPK**2
      GO TO 103
  102 PRLPK=DNSARI*.016126*VHLPK*VNOM**2
      VPK=VNOM
  103 PRLOT=CDOT*DNSARO*.016126*ADOT*VOT**2
      PRLSL=CDSL*DNSARO*.016126*ADSL*VSL**2
      PRLVC=VHVC*DNSARI*.016126*VNOM**2
      PRLSP=VHSP*DNSARI*.016126*VNOM*VNOM
      PRLPR=PRLOT+PRLIN+PRLSL
      H=(PRLPR+PRLPK+PRLSP+PRLVC)/(DNSARI-DNSARO)
      IF(ENDFLG)GO TO 40
      NOITER=NOITER+1
      IF(.NOT.PRITER.OR.EXTAFL)GO TO 21
   40 IF(LITER.LT.52)GO TO 30
      LSTEP=50
      LITER=0
      IPG=IPG+1
      WRITE(6,31)JM,JD,JY,IPG
   31 FORMAT(#1COOLING TOWER PROGRAM  -  RESULTS OF ITERATIONS#,53X,
     *  I2,2(1H/I2),# PAGE#,I3/#0#22X,#AIR  CALC   TOWER#/
```

```
     *#          OUTLET  VELCTY HEAT  CHARAC-   SKIN          INLET#,
     *# OUTLET OUTLET PROFILE  PACKING    SPRAY  VENA CON#/
     *# ITER  WATER   AIR     IN    TRANS TERISTIC FRICTION RELAT WATER#
     *#  AIR    AIR   PRESSURE PRESSURE PRESSURE PRESSURE TOWER#/
     *#  NO   LOSS  DENSITY PAKING COEFF (K*A/L)   COEFF   HUMID TEMP #,
     *#  TEMP  ENTHAL   LOSS     LOSS     LOSS     LOSS    HEIGHT#)
   30 WRITE(6,32)NOITER,WTRLT,DNSARO,VPK,HBOUT,KAL,CF,HUMI,WTRT,AIRT,
     *  ENT,PRLPR,PRLPK,PRLSP,PRLVC,H
   32 FORMAT(#0#,I4,F7.2,F8.6,F7.3,F6.3,F8.4,F9.5,F7.3,F6.1,
     *  F6.1,F7.1,F10.6,3F9.6,F7)
      LITER=LITER+2
      IF(ENDFLG)GO TO 33
C*********************************************************************
C     END PRINTING RESULTS OF ONE ITERATION
C*********************************************************************
   21 IF(NOITER.LE.100)GO TO 39
      WRITE(6,98)
   98 FORMAT(#-MORE THAN 100 ITERATIONS.  EXECUTION TERMINATED#)
      STOP
C*********************************************************************
C     NOW FIND IF SPECIFICED TOLERANCES ARE MET, AND IF NOT, WHICH
C     OF AIRF OR WTRTO SHOULD BE ADJUSTED
C  PRINT A MESSAGE WHICH SHOWS VALUE FROM WHICH A NEW VALUE WILL
C  BE EXTRAPOLATED
C*********************************************************************
   39 IF(ABS(WTRT-WTRTI).LE.TOLERT)GO TO 27
      IF(.NOT.PRITER)GO TO 46
      IF(.NOT.EXTAFL)GO TO 48
      WRITE(6,42)WTRTO
   42 FORMAT(#      (EXTRAPOLATING FROM WTRTO=#,F6.1,#)#)
      LITER=LITER+1
      GO TO 46
   48 WRITE(6,43)WTRTO
      LITER=LITER+2
   43 FORMAT(#0(EXTRAPOLATING FROM WTRTO=#,F6.1,#)#)
   46 WTRT1=WTRT
      WTRTO=WTRTO+.001
      EXTWTO=.TRUE.
      GO TO 15
   27 IF(EXTAFL)GO TO 50
      IF(ABS(H-HTOWER).LE.TOLERH)GO TO 29
      IF(.NOT.PRITER)GO TO 44
      WRITE(6,41)AIRF
      LITER=LITER+2
   41 FORMAT(#0(EXTRAPOLATING FROM AIRF=#,F7.1,#)#)
   44 AIRFL=AIRF
      H1=H
      AIRF=AIRF+10.
      EXTAFL=.TRUE.
      GO TO 95
C*********************************************************************
C     A SAMPLE ITERATION HAS BEEN MADE TO ADJUST AIRF OR WTRTO
C     PRINT MESSAGE, AND DO ANOTHER ITERATION
C*********************************************************************
   50 H2=H
      DAFDH=10./(H2-H1)
```

```
      EXTAFL=.FALSE.
      AIRF=AIRF+DAFDH*(HTOWER-H)
      IF(.NOT.PRITER)GO TO 95
      WRITE(6,55)AIRF
      LITER=LITER+1
   55 FORMAT(≠  (MODIFYING AIRF TO ≠,F7.1,≠)≠)
      GO TO 95
   24 WTRT2=WTRT
      DTODTI=.001/(WTRT2-WTRT1)
      EXTWTO=.FALSE.
      WTRTO=WTRTO+DTODTI*(WTRTI-WTRT)
      IF(.NOT.PRITER)GO TO15
      IF(.NOT.EXTAFL)GO TO 62
      WRITE(6,61)WTRTO
   61 FORMAT(≠        (MODIFYING WTRTO TO ≠,F6.1,≠)≠)
      LITER=LITER+1
      GO TO 15
   62 WRITE(6,60)WTRTO
      LITER=LITER+2
   60 FORMAT(≠  (MODIFYING WTRTO TO ≠,F6.1,≠)≠)
      GO TO 15
   29 IF(PRITER)GO TO 33
      ENDFLG=.TRUE.
      LITER=52
      GO TO 100
   33 WRITE(6,96)WTRTO,H
   96 FORMAT(≠-END COOLING TOWER PROGRAM≠/
     *  ≠OFINAL OUTLET WATER TEMPERATURE IS≠,F6.1/
     *  ≠OFINAL TOWER HEIGHT IS≠,F7.0)
      STOP
  110 AIRF=(AIRF-AIRFL)/2.+AIRFL
      IF(.NOT.PRITER)GO TO 95
      WRITE(6,111)AIRF
      LITER=LITER+2
  111 FORMAT(≠O(ADJUSTING AIRF TO≠,F7.1,≠ FOR --ABILITY)≠)
      GO TO 95
      END
```

```
      FUNCTION PSAT(T)
      DIMENSION V(181)
      DATA M/0/
      DATAV/.08854,.09223,.09603,.09995,.10401,.10821,.11256,.11705,.121
     *70,.12652,.13150,.13665,.14199,.14752,.15323,.15914,.16525,.17157,
     *.17811,.18486,.19182,.19900,.20642,.2141,.2220,.2302,.2386,.2473,.
     *2563,.2655,.2751,.2850,.2951,.3056,.3164,.3276,.3390,.3509,.3631,.
     *3756,.3886,.4019,.4156,.4298,.4443,.4593,.4747,.4906,.5069,.5237,.
     *5410,.5588,.5771,.5959,.6152,.6351,.6556,.6766,.6982,.7204,.7432,.
     *7666,.7906,.8153,.8407,.8668,.8935,.9210,.9492,.9781,1.0078,1.0382
     *,1.0695,1.1016,1.1345,1.1683,1.2029,1.2384,1.2748,1.3121,1.3504,1.
     *3896,1.4298,1.4709,1.5130,1.5563,1.6006,1.6459,1.6924,1.7400,1.788
     *8,1.8387,1.8897,1.9420,1.9955,2.0503,2.1064,2.1638,2.2225,2.2826,2
     *.3440,2.4069,2.4712,2.5370,2.6042,2.6729,2.7432,2.8151,2.8886,2.96
     *37,3.0404,3.1188,3.1990,3.281,3.365,3.450,3.537,3.627,3.718,3.811,
     *3.906,4.003,4.102,4.203,4.306,4.411,4.519,4.629,4.741,4.855,4.971,
     *5.090,5.212,5.335,5.461,5.590,5.721,5.855,5.992,6.131,6.273,6.417,
     *6.565,6.715,6.868,7.024,7.183,7.345,7.510,7.678,7.850,8.024,8.202,
     *8.383,8.567,8.755,8.946,9.141,9.339,9.541,9.746,9.955,10.168,10.38
     *5,10.605,10.830,11.058,11.290,11.526,11.769,12.011,12.262,12.512,1
     *2.771,13.031,13.300,13.568,13.845,14.123,14.410,14.696/
      NT=T
      PSAT=0.
      IF(NT.GT.31)GO TO 5
      PSAT=V(1)
      WRITE(6,2)T
    2 FORMAT(*0ERROR IN PSAT: TABLE EXCEEDED.  T=*,F8.2)
    4 M=M+1
      IF(M.LE.50)RETURN
      WRITE(6,3)
    3 FORMAT(*0 MORE THAN 50 ERRORS IN PSAT -- EXECUTION TERMINATED*)
      STOP
    5 IF(NT.GE.212)GO TO 4
    1 PSAT=V(NT-31)+(V(NT-30)-V(NT-31))*(T-NT)
      RETURN
      END
```

SAMPLE OUTPUT

COOLING TOWER PROGRAM - LISTING OF INITIAL VARIABLES

VARIABLE NAME	VALUE
WTRTI	97.000000 *
AIRTI	90.000000 *
HTOWER	350.000000 *
DTOWER	300.000000 *
HAIRIN	20.000000 *
HUM	0.370000 *
WTRFT	84822960.000000 *
WTRF	1199.999756 *
AIRF	1199.999756 *
WTRTO	72.000000 *
STEPS	20.000000 *
TOLERT	0.100000 *
TOLERH	10.000000 *
AFIN	1.000000 *
AFOT	1.000000 *
AFSL	1.000000 *
ADIN	0.0 *
ADOT	0.0 *
ADSL	0.0 *
CDIN	0.0 *
CDOT	0.0 *
CDSL	0.0 *
CP	0.240000 *
ATMOS	14.492999 *
DNSARI	0.070712 *

(PARALLEL PLATE PACKING ASSUMED)

ATOTAL	235.000000 *
AFPK	0.750000 *
ADPK	314.000000 *

*VALUE CALCULATED FROM OTHER INPUT OR ASSUMED

COOLING TOWER PROGRAM - RESULTS OF ITERATIONS

ITER NO	WATER LOSS	OUTLET AIR DENSITY	AIR VELCTY IN PAKING	CALC HEAT TRANS COEFF	TOWER CHARAC-TERISTIC (K*A/L)	SKIN FRICTION COEFF	RELAT HUMID	INLET WATER TEMP	OUTLET AIR TEMP	OUTLET AIR ENTHAL	PROFILE PRESSURE LOSS	PACKING PRESSURE LOSS	SPRAY PRESSURE LOSS	VENA CON PRESSURE LOSS	TOWER HEIGHT
1	6.07	0.072124	6.223	1.639	1.3370	0.01920	0.791	74.5	77.6	28.9	0.0	0.268895	0.081085	0.952113	-922.
(EXTRAPOLATING FROM WTRTO= 72.0)															
(MODIFYING WTRTO TO 82.4)															
2	22.33	0.069609	6.335	1.639	1.3370	0.01920	0.874	103.6	92.8	47.5	0.0	0.273714	0.081085	0.952113	1185.
(EXTRAPOLATING FROM WTRTO= 82.4)															
(MODIFYING WTRTO TO 80.7)															
3	18.31	0.070106	6.312	1.639	1.3370	0.01920	0.853	97.4	89.9	43.1	0.0	0.272749	0.081085	0.952113	2155.
(EXTRAPOLATING FROM WTRTO= 80.7)															
(MODIFYING WTRTO TO 80.5)															
4	18.04	0.070141	6.311	1.639	1.3370	0.01920	0.851	97.0	89.7	42.8	0.0	0.272681	0.081085	0.952113	2288.
(EXTRAPOLATING FROM AIRF= 1200.0)															
(EXTRAPOLATING FROM WTRTO= 80.5)															
(MODIFYING WTRTO TO 80.5)															
(MODIFYING AIRF TO 885.8)															
7	12.14	0.070459	4.648	1.364	1.1129	0.02235	0.865	91.2	87.6	40.8	0.0	0.172538	0.065959	0.518761	2991.
(EXTRAPOLATING FROM WTRTO= 80.5)															
(MODIFYING WTRTO TO 83.0)															
8	15.49	0.069846	4.668	1.364	1.1129	0.02235	0.883	97.4	91.2	45.9	0.0	0.173291	0.065959	0.518761	875.
(EXTRAPOLATING FROM WTRTO= 83.0)															
(MODIFYING WTRTO TO 82.8)															
9	15.27	0.069884	4.667	1.364	1.1129	0.02235	0.882	97.0	91.0	45.6	0.0	0.173243	0.065959	0.518761	916.
(EXTRAPOLATING FROM AIRF= 885.8)															
(EXTRAPOLATING FROM WTRTO= 82.8)															
(MODIFYING WTRTO TO 82.7)															
(MODIFYING AIRF TO 686.4)															
12	11.01	0.070145	3.610	1.168	0.9530	0.02539	0.892	92.7	89.3	43.8	0.0	0.117965	0.055460	0.311533	855.
(EXTRAPOLATING FROM WTRTO= 82.7)															
(MODIFYING WTRTO TO 84.9)															
13	13.28	0.069633	3.623	1.168	0.9530	0.02539	0.905	97.4	92.3	48.2	0.0	0.118396	0.055460	0.311533	450.
(EXTRAPOLATING FROM WTRTO= 84.9)															
(MODIFYING WTRTO TO 84.7)															

ITER NO	WATER LOSS	OUTLET AIR DENSITY	AIR VELCTY IN PAKING	CALC HEAT TRANS COEFF	TOWER CHARAC- TERISTIC (K*A/L)	SKIN FRICTION COEFF	RELAT HUMID	INLET WATER TEMP	OUTLET AIR TEMP	OUTLET AIR ENTHAL	PROFILE PRESSURE LOSS	PACKING PRESSURE LOSS	SPRAY PRESSURE LOSS	VENA CON PRESSURE LOSS	TOWER HEIGHT
14	13.08	0.069676	3.622	1.168	0.9530	0.02539	0.904	97.0	92.1	47.9	0.0	0.118360	0.055460	0.311533	468.

(EXTRAPOLATING FROM AIRF= 686.4)
(EXTRAPOLATING FROM WTRTO= 84.7)
(MODIFYING WTRTO TO 84.6)
(MODIFYING AIRF TO 617.7)

17	11.37	0.069800	3.256	1.095	0.8935	0.02676	0.908	95.2	91.3	46.9	0.0	0.100948	0.051621	0.252275	444.

(EXTRAPOLATING FROM WTRTO= 84.6)
(MODIFYING WTRTO TO 85.5)

18	12.21	0.069593	3.261	1.095	0.8935	0.02676	0.913	97.0	92.5	48.8	0.0	0.101097	0.051621	0.252275	362.

(EXTRAPOLATING FROM AIRF= 617.7)
(EXTRAPOLATING FROM WTRTO= 85.5)
(MODIFYING WTRTO TO 85.3)
(MODIFYING AIRF TO 609.3)

21	11.89	0.069634	3.216	1.086	0.8860	0.02695	0.913	96.6	92.3	48.4	0.0	0.099006	0.051140	0.245437	367.

(EXTRAPOLATING FROM WTRTO= 85.3)
(MODIFYING WTRTO TO 85.6)

22	12.11	0.069581	3.217	1.086	0.8860	0.02695	0.914	97.0	92.6	48.9	0.0	0.099043	0.051140	0.245437	350.

END COOLING TOWER PROGRAM

FINAL OUTLET WATER TEMPERATURE IS 85.6

FINAL TOWER HEIGHT IS 350.

BIBLIOGRAPHIC: Winiarski, L.D., Tichenor, B. A., Byram, K.V., "A Method for Predicting the Performance of Natural Draft Cooling Towers," Environmental Protection Agency, National Thermal Pollution Research Program, Report No. 16130 GKF 12/70, December 1970.

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ABSTRACT: A method is developed for analyzing the performance of counterflow and crossflow natural draft cooling towers that does not assume saturated air at the top of the packing. Types of cooling towers and the principles of operation are considered. Simplified differential equations for the heat and mass transfer relations and the methods of integrating them for both counterflow and crossflow towers are given. A large number of integration steps is shown to be unnecessary. Equations for estimating the pressure losses in the tower are also given. Simplified flow charts using these integration schemes show how the computer program is used to evaluate tower performance. The computed performance of towers of various heights operating in moist and in dry conditions is shown. The effect of inlet water temperature is shown to be significant. Finally, the computed performance of a given tower with fixed inlet water temperature is shown as a function of relative humidity and dry bulb air temperature.

KEY WORDS:

Cooling towers,
Water cooling
Thermal pollution
Thermal powerplants
Energy dissipation
Evaporation

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1 Accession Number	2 Subject Field & Group	
	Ø13E	**SELECTED WATER RESOURCES ABSTRACTS** INPUT TRANSACTION FORM

5 *Organization*
Water Quality Office, Environmental Protection Agency, Pacific Northwest Water Laboratory, Corvallis, Oregon

6 *Title*
A METHOD FOR PREDICTING THE PERFORMANCE OF NATURAL DRAFT COOLING TOWERS

10 *Author(s)*
Winiarski, Lawrence D.
Tichenor, Bruce A.
Byram, Kenneth V.

16 *Project Designation*
16130 GKF 12/70

21 *Note*

22 *Citation* Environmental Protection Agency, National Thermal Pollution Research Program Report No. 16130 GKF 12/70, December 1970. 69 p., 13 fig, 3 tab, 8 ref.

23 *Descriptors (Starred First)*
*Cooling towers, *Water cooling *Thermal pollution, thermal power plants Energy dissipation, evaporation

25 *Identifiers (Starred First)*
*Natural draft

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