$\Delta P/L$ = pressure drop per unit length, $lb._{(f)}$/cu. ft.
Q_T = total heat flux across an interface, B.t.u./hr. sq.ft.
Q_L = heat flux to felt through liquid transport, B.t.u./hr. sq.ft.
Q_V = heat flux to felt through vapor transport, B.t.u./hr. sq.ft.
Q_1 = dimensionless heat flux between sheet and felt, dimensionless
Q_2 = dimensionless heat flux between felt and air, dimensionless
Q_3 = dimensionless heat flux between surface and sheet, dimensionless
q = heat flux, B.t.u./hr. sq.ft.
R_1 = Nusselt modulus based on h_1, dimensionless
R_2 = Nusselt modulus based on h_2 and sheet properties, dimensionless
R_3 = Nusselt modulus based on h_2 and felt properties, dimensionless
R_4 = Nusselt modulus based on h_4, dimensionless
r = relative distance in sheet from cylinder, dimensionless
S = perimeter of capillary, ft.
t = temperature, °R.
t_B = base temperature on an absolute scale, °R.
t_o = initial temperature, °R.
t_s = cylinder surface temperature, °R.
t_{sn} = temperature in the sheet at the nth level, °R.
t_{fn} = temperature in the felt at the nth level, °R.
t_a = air temperature, °R.
t_1 = initial average felt temperature, °R.
t_2 = final average felt temperature, °R.
t'_{so} = initial average sheet temperature, °R.
$\overline{t_t}$ = average temperature at which liquid is transferred to the felt, °R.
$\bar{u}$ = average velocity of liquid in a capillary, ft./hr.
V = velocity of sheet, ft./hr.
v = $H(dH)/(d\theta)$, sq.ft./hr.
X = thickness of sheet, ft.
x = distance through thickness of sheet, ft.
y = distance across width of sheet, ft.
z = distance along length of sheet, ft.

Greek Letters

α = thermal diffusivity, sq.ft./hr.
γ = surface tension, $lb._{(f)}$/ft.
δ = thickness of felt, ft.
ϵ = emissivity, dimensionless
ξ = mass of moisture entering the felt, $lb._m$/hr. sq.ft.
η = fraction of moisture entering the felt as a liquid, dimensionless
θ = time, hr.
Ψ = contact angle, radians
λ = latent heat of vaporization, B.t.u./$lb._m$
ϕ = angle of inclination of capillary to the horizontal, radians
μ = viscosity, $lb._m$/hr.-ft.
ρ = density, $lb._m$/cu.ft.
σ = Stefan-Boltzmann constant, B.t.u./hr.-sq.ft.-°R.^{4}
τ_f = Fourier modulus based on felt properties, dimensionless
τ_s = Fourier modulus based on sheet properties, dimensionless

Subscripts

f = property of felt
s = property of sheet
x = property in the x direction
y = property in the y direction
z = property in the z direction

LITERATURE CITED

1. Bell, J. R., W. F. E. Robinson, and A. H. Nissan, *Tappi*, **40**, 558 (1957).
2. Brauns, O., and S. Ponton, *Svensk Papperstidning*, **62**, 245 (1959).
3. Carslaw, H. S., and J. C. Jaeger, "Conduction of Heat in Solids," 2 ed., Oxford Press, London, England (1959).
4. Nissan, A. H., *Tappi*, **37**, 597 (1954).
5. ———, and David Hansen, *A.I.Ch.E. Journal*, **6**, 606 (1960).
6. Nissan, A. H., and W. G. Kaye, *Tappi*, **38**, 385 (1955).
7. Palmer, W. B., *J. Textile Inst.*, **44**, T391 (1953).
8. Smith, S. F., and R. W. Atwood, *Tappi*, **36**, 481 (1953).

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Energy Balances in Solar Distillers

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There has been considerable doubt as to the manner in which the productivity of solar stills is affected by many of the designs and operating variables. To assist in designing solar stills of improved performance, theoretical equations are derived to describe the complete energy and mass transfer relationships involved in the operation of the basin type of solar still. These are supplemented with data from field operation of a 2,500-sq. ft. still. With these relationships and the aid of a digital computer, the effects of variations of design parameters on the performance of solar stills is predicted. Distiller productivity is correlated with atmospheric temperature, wind velocity, solar radiation, absorptivity and slope of transparent cover, and other variables. Curves showing the magnitude of the effects of design changes on cover temperature, brine temperature, and productivity are presented.

Although superficially a simple process the production of fresh water from sea water by solar distillation in basin types of distillers involves a complex set of operations comprising radiant and convective heat transfer, thermal conduction, vapor diffusion, evaporation and condensation, and other phenomena all taking place inside one piece of equipment. Even though the first practical solar distillation unit was built almost 90 yr. ago (2), a complete quantitative evaluation of these energy and mass transfer relationships has never been reported. The designing of this first

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plant and of the recent pilot plants in this country and abroad was largely empirical. In the evaluation of the performance of these units correlation of productivity with other variables has been attempted, but the numerous uncontrollable conditions, such as solar radiation, atmospheric temperature, and wind velocity have complicated the analysis. Design parameters such as distiller shape, water depth, type of covering material, and so on have not been evaluated quantitatively because of the inability to make design changes in existing units.

In the approach to the problem discussed here complete energy and mass transfer relationships were formulated. The use of a computer made it possible, through the substitution of wide ranges of atmospheric design and operating variables, to determine the theoretical performance of basin types of distillers as affected by each of the variables. Information about these significant relationships can be used in evaluating the desirability of making specific changes in the design and operation of distillers. However the numerical values of certain parameters in the energy-balance equations could not be ascertained through computer simulation. Needed empirical data were obtained at the well-instrumented pilot plant at Daytona Beach, Florida. Detailed energy-balance measurements over three ranges of solar radiation intensity yielded information against which the theoretical performance could be checked and by which the specific effects of atmospheric variables could be observed.

Solar distillation equipment and the manner of its operation have been amply described in the literature (5, 9). Therefore only the general principle will be repeated here. Two applications of the principle will be described.

Figure 1 shows a pond of saline water about 1 ft. deep. The basin is lined with an impervious material, such as asphalt, and is provided with concrete side walls and partition walls which subdivide it into long narrow sections. Plates of ordinary window glass are supported by the partition walls and ridge beams at an angle of about 15 deg. with the horizontal. These are arranged so that condensation on the glass plates may drain into small troughs supported by the partition walls. The solar radiation incident on the black bottom of the pond heats the saline water in the basin, and vaporization into the enclosed air space takes place. The mixture of air and water vapor circulates inside the enclosure, coming into contact with the cooler glass covers on which the vapor condenses. The heat of condensation is dissipated to the atmosphere by convection and radiation. Condensate collects in the troughs and drains to storage, while the unevaporated brine is discharged to waste. Water is maintained at a constant level in the basin through controlled addition of sea water.

Figure 2 shows another form of this type of distiller in which the depth of the water in the basin is only an inch or two. Instead of the structurally supported glass cover there is an air-supported transparent plastic film. However the principle of operation is the same as that of the glass-covered still.

The advantage in the solar distillation process is the extremely low operating cost, primarily because purchase of energy is not required. However the low-energy intensity of sunlight compared with that of conventional energy sources makes necessary large areas for heat and mass transfer. The maximum solar energy heat transfer rates of 300 B.t.u./(hr.) (sq. ft.) seem extremely small when compared with the rates of perhaps 25,000 B.t.u./(hr.) (sq. ft.) in good heat transfer equipment with which the engineer is familiar. It is therefore necessary to take every possible step to minimize the cost of the solar still installation. For the same reason maximum productivity is essential. Current engineering effort and pilot-plant developments are minimizing installation costs. Analyses of the type presented in this discussion should lead to improvements in productivity.

SOLAR DISTILLATION THEORY

The complexity of the energy transfer relationships in a basin type of solar still is illustrated in Figure 3. As shown, part of the direct and diffuse solar radiation reaching the still is reflected or absorbed by the cover. Part of it is reflected from water surface and basin bottom. Also part of it is absorbed in the water itself. The rest is absorbed on the basin bottom. Most of the radiation incident on the basin bottom is absorbed by the saline water; a small portion is lost by conduction to the ground. The heated saline water then loses energy by several processes. Radiation from the water surface is either absorbed or transmitted by the cover, depending upon the properties of the cover. Glass for example is opaque to long wave radiation and completely absorbs that emitted from the water surface. Energy is also transferred from water to cover by convection through air and by alternate vaporization and condensation of water. It is this last energy transfer, the latent heat of the water vapor transferred from the basin to the cover, which is useful in the system.

The energy which is transferred to the cover is conducted through it and is dissipated to the atmosphere by radiation and convection. There may also be some sensible heat supplied to the still in the feed water and some sensible heat lost in the condensate and brine. Any leakage of vapor or liquid from the distiller involves additional thermal loss. Finally, since solar radiation intensity and other factors are continually changing, there is an increase or decrease in the enthalpy of the distiller and its contents.

The energy transfer rate relationships described above may be fully represented by a complete energy balance on the entire distillation unit:

$$I_o = I_o \Sigma r + (A_c/A_p)[h_o(t_c - t_a) + 0.173 \times 10^{-8} (T_c^4 - T_s^4)\epsilon_c] + (A_{st}/A_p)\,[h_o(t_{st} - t_a) + 0.173 \times 10^{-8}(T^4_{st} - T^4_s)\bar{\epsilon}_{st}] + DH_{d,t_p} + BH_{b,t_b} + L_b H_{b,t_b'} + L_d H_{d,t_d'} + L_v H_{v,t_v'} + L_a C_{pa}(t_v' - t_a) - (D + B + L_b + L_d + L_v)\, H_{sw,t_o} + (\overline{k/l})\,(t_w - t_{gr}) + (A_w/A_p)\, [0.173 \times 10^{-8}(T_w^4 - T_s^4)\, \epsilon_w\, Tr_c] + (A_{i,st}/A_p)\, [0.173 \times 10^{-8}(\overline{T}^4_{i,st} - T^4_s)\, \epsilon_{st}\, Tr_c] + \Delta\Sigma H_p/A_p \quad (1)$$

The only assumptions on which this equation rests are that there are no temperature gradients in the *cover* and that there are no temperature gradients in the basin. The former is justified because of the low thermal flux and the thin cover material; the latter is justified because of the overall design and operating uniformity.

If it is assumed that temperature drop through the condensate film is negligible and that the portion of the hemispherical radiation from the cover which is intercepted by other parts of the cover is negligible, the following energy balance around the cover can be written:

$$(A_c/A_p)[h_o(t_c - t_a) + 0.173 \times 10^{-8} (T_c^4 - T_s^4)\epsilon_c] = h_i(t_w - t_c)(A_w/A_p) + (A_w/A_p)\,[0.173 \times 10^{-8}\,(T_w^4 - T_c^4) \times F_{wc}] + \frac{A_p - A'_{st}}{A_p} I_o\, \bar{\alpha}_{c,s} + (D + L_d + d + r)\,(H_{v,t_v} - H_{d,t_d}) + q_{st-c} + h_i'(\bar{t}_{i,st} - t_c)\,(A_{i,st}/A_p) + (A_{i,st}/A_p)[0.173 \times 10^{-8}(\overline{T}^4_{i,st} - T^4_c) \times F_{i,st-c}] \quad (2)$$

The above relationship equates the rate of heat dissipation from the cover to the atmosphere by convection and radiation to the energy the cover receives by air convection inside the distiller, thermal radiation from the water surface, absorption of direct and reflected solar radiation in the cover material, latent heat of condensation of water vapor, thermal conduction, convection, and radiation from internal structures on which the cover rests. The absorption of radiation by the water vapor in the air inside the still is small and can be neglected.

A third equation can be written for the evaporation rate in the distillation unit:

$$(A_p/A_w)\,(D + L_d + d + r)\,C_{p_a}\,(t_{a_1} - t_{a_2})\,M_a/M_{H_2O} = h_i(t_w - t_c) \quad (3)$$

In this equation the first two factors represent the total condensation rate on the cover. When multiplied by heat capacity, air temperature rise, and ratio of air circulated to water condensed the left side of the equation represents the heat transfer rate by means of circulating air. This is set equal to an equivalent term involving the internal convection coefficient.

If appropriate design and performance data are used (or if hypothetical values are chosen), these three equations can be employed in appraising the specific effect on performance of each variable. In this analysis information concerning pilot-plant performance was employed, both as a guide in making simplifying assumptions and as a means for evaluating certain constants and ranges of variables. The following section contains a summary of the experimental design and test data.

EXPERIMENTAL EVALUATION OF A BASIN TYPE OF SOLAR STILL

Design and Long-Term Performance

A deep-basin solar still of a design comparable to that described by the preceding theoretical equations was built in 1958 at the Solar Distillation Research Station at Daytona Beach, Florida, which is being operated by the Battelle Memorial Institute for the Office of Saline Water (*1*). The unit has been in operation approximately 16 mo. during which time extensive data on distillate production and on energy and mass balances have been acquired. Figure 1 shows the general features of this installation.

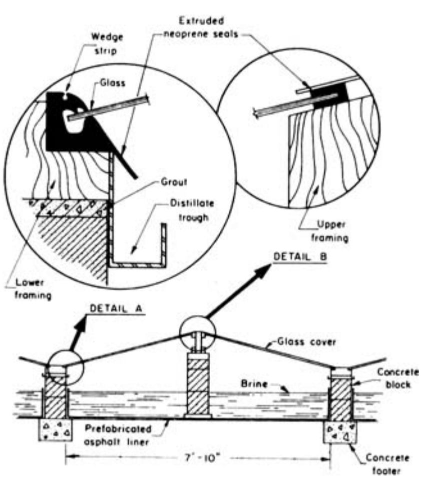

Fig. 1. Cross section of glass-covered deep-basin solar still.

The still, which is approximately 55 ft. sq. provides 2,450 sq. ft. of basin area. The cover consists of 4-ft.-sq. window-glass panels sloped at an angle of 15 deg. The upper edges of the glass panels rest on timber beams supported by concrete block pillars. The basin of the still was made watertight by placing ½ in. thick prefabricated asphalt mats directly on the soil and on the inside surfaces of the still walls. Foam-glass insulation was placed around the perimeter walls so that the edge heat losses would be small and therefore comparable to the losses of much larger stills.

Figure 4 shows the average monthly productivity of the still at various solar radiation intensities, as obtained in 16 mo. operation of the unit. The average depth of water in the basin during the time the data were obtained was about 6 in. The nearly linear relationship implies that the rate of distillate production is dependent primarily on the amount of solar radiation. However, as is shown subsequently, there are major short-duration influences due to ambient air temperature and wind velocity which disappear when long-term averages are used in the calculation and when there is considerable heat storage in the basin water.

Distribution of Energy

Several complete energy and mass balances have been conducted on the deep-basin still. The runs usually covered a 3-day period, during which measurements of flow rates and temperatures were obtained in great detail. From such balances it is possible to locate losses in the still, to appraise their relative importance, and to gain insight as to the improvements that might be made in still design.

Table 1 shows the results of three energy and mass balances conducted on the deep-basin still. These particular examples were selected to show the effects of widely different solar radiation intensities. As shown, about 25 to 40% of the available solar energy was utilized to produce distillate. The largest single loss was thermal radiation from the basin water to the still cover. The loss decreased from 36% at the lowest solar radiation intensity to about 17% at the highest intensity. Simultaneously the over-all thermal efficiency increased from 24.5 to 40.5%. These figures emphasize the important effect of this loss on still performance and show the main reason for the trend, usually noted in solar stills, of thermal efficiency increase with solar radiation increase. Of particular interest is the relatively low magnitude of the heat loss to the ground from the uninsulated large basin. The indicated loss by internal convection does not appear excessive, but 90% saturation was assumed in the calculation. The subsequent theoretical analyses of these data indicated considerably lower vapor-to-air ratios prevailed. Hence the convection losses are also of major importance. Possibly much of the energy which is not accounted for in Table 1 is actually additional convection loss.

COMPUTATION OF RESULTS

The three rigorous equations previously developed contain numerous de-

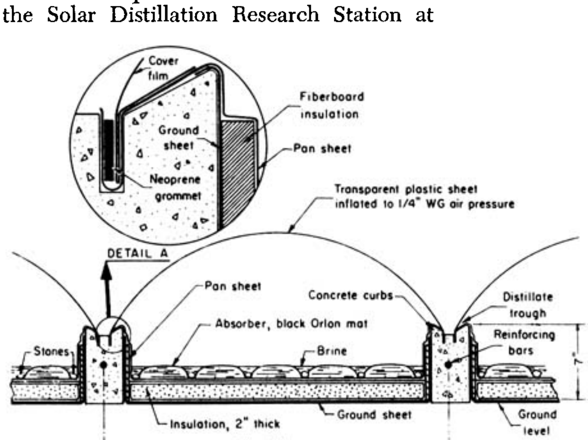

Fig. 2. Cross section of air-supported plastic solar still.

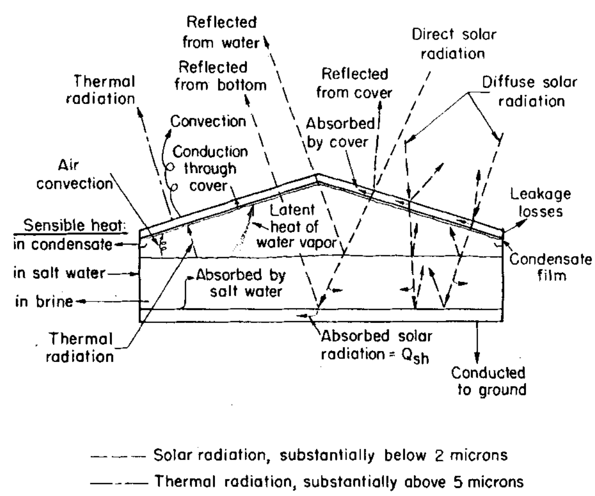

Fig. 3. Energy-flow diagram of a basin type of solar still.

TABLE 1. DISTRIBUTION OF SOLAR RADIATION* INCIDENT ON DEEP-BASIN STILL

	Dates of three-day performance runs		
	Dec. 16-18, 1959	Oct. 7-9, 1959	May 18-20, 1960
Average solar radiation, B.t.u./(sq. ft.)(day)	756	1,400	2,318
Average air temperature, °F.	76	79	77
Average cover temperature, °F.	71	89	98
Average brine temperature, °F.	82	102	111
Average productivity, gal./(sq. ft.)(day)	0.021	0.051	0.105
Components	Percentage of solar radiation		
Reflection	11.8	10.7	11.8
Absorption by glass cover	4.1	4.6	4.4
Net radiation from water	36.0	26.4	16.9
Internal convection†	13.6	7.9	8.4
Ground and edge losses	2.1	1.6	3.5
Distillation	24.5	32.2	40.5
Re-evaporation and unaccounted for	7.9	16.6	14.5
	100.0	100.0	100.0

* Instrumentation and methods used to determine distribution of energy are described in reference *10*.

† Assuming saturation at cover temperature and 90% relative humidity at brine temperature.

Note: Energy resulting from heat storage in brine was divided proportionately among net radiation from water, distillation, and internal convection.

sign and operating parameters, some of which may be combined or eliminated if information relative to the experimental still is used. For example the leakage items can be eliminated, because if the equation is being applied to ideal operation, these items should not be present. Other terms, such as the internal convection coefficient, may be related to temperature. In other instances choice of a particular design eliminates some of the terms. For example with glass covers there is no thermal radiation from the water through the cover.

By application of these and other substitutions and simplifications, as shown in the Appendix, the following equations may be derived:

Over-all energy balance:

$$I_o(1-\Sigma r) = (A_c/A_p)[h_o(t_c-t_a) + 0.173\times10^{-8}[T_c^4-(fT_a)^4]\,0.94] + 0.50\,I_o(A'_{st}/A_p) + DH_{d,t_b} + 0.45\,DH_{d,t_b} - 55.5\,D + (2.2/\sqrt{A_p})(t_w-75) + \left(\frac{A_w+A_{t,st}}{A_p}\right)[0.173\times10^{-8}[T_w^4-(fT_a)^4]\,0.96\,Tr_c] \quad (1a)$$

Energy balance around cover:

$$(A_c/A_p)[h_o(t_c-t_a) + 0.173\times10^{-8}[T_c^4-(fT_a)^4]\,0.94] = \left(\frac{A_w+A_{t,st}}{A_p}\right) C(t_w-t_c)^{4/3} + \frac{A_w+A_{t,st}}{A_p}[0.173\times10^{-8}(T_w^4-T_c^4)\,0.85] + \frac{A_p-A'_{st}}{A_p} I_o\,\bar{\alpha}_{c,s} + D(1+K)\,1{,}040 \quad (2a)$$

Evaporation rate:

$$(A_p/A_w)(1+K)D = \frac{C}{0.24}(t_w-t_c)^{1/3}F(W_{s,w}-W_{s,c}) \quad (3a)$$

In these simplified equations four new factors have been introduced. The term f relates to atmospheric temperature and the effective temperature for radiation to space; K is a factor for dripping of condensate back into the basin and evaporation of the condensate from the collection troughs; F represents the degree of approach to thermal and humidity equilibrium at the saline water and fresh water surfaces, and C is a variable coefficient in the relationship for the convection coefficient inside the still.

To reduce the number of necessary calculations the only case considered was the one in which no external heat exchange takes place between the effluent brine and the distillate and feed water. This represents the operation of the stills at the Florida station. Thus comparisons between theoretical and actual performance can be made.

By substituting into Equation (1*a*) the values of the variables determined in the energy balances on the experimental stills, it was found that the terms

$$DH_{d,t_p} + 0.45\,DH_{b,t_b} - 55.5\,D + \frac{2.2}{\sqrt{A_p}}(t_w-75)$$

totaled less than 4% of the energy involved and that they could be neglected with no significant error. Also the glass cover of a still, or the water film on a plastic cover, absorbs all the long-wave radiation from the water surface, so the last term in Equation (1*a*) is negligible:

$$\frac{A_w+A_{t,st}}{A_p}[0.173\times10^{-8}[T_w^4-(fT_a)^4]\times0.96\times Tr_c]$$

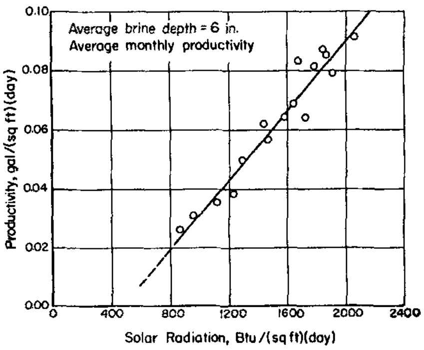

Fig. 4. Productivity of the deep-basin still obtained during 16 months of operation of the still.

Equation (1*a*) can then be simplified to

$$I_o(1-\Sigma r-0.50\,A'_{st}/A_p) = \frac{A_c}{A_p}[h_o(t_c-t_a) + 0.173\times10^{-8}[T_c^4-(fT_a)^4]\times0.94] \quad (1b)$$

It is apparent that the right side of Equation (1*b*) is the same as the left side of Equation (2*a*). Equation (2*a*) can therefore be written as

$$I_o(1-\Sigma r-0.50\,A'_{st}/A_p) = \frac{A_w+A_{t,st}}{A_p}C(t_w-t_c)^{4/3} + \frac{A_w+A_{t,st}}{A_p}[0.173\times10^{-8}(T_w^4-T_c^4)\times0.85] + \frac{A_p-A'_{st}}{A_p}I_o\,\bar{\alpha}_{c,s} + D(1+K)(1040) \quad (2b)$$

and Equation (3*a*) can be written as

$$D = \frac{C(t_w-t_c)^{1/3}F(W_{s,w}-W_{s,c})}{(A_p/A_w)(1+K)(0.24)} \quad (3b)$$

If one substitutes Equation (3*b*) into Equation (2*b*), Equation (2*b*) becomes

$$I_o(1-\Sigma r-0.50\,A'_{st}/A_p) = \frac{A_w+A_{t,st}}{A_p}C(t_w-t_c)^{4/3} + \frac{A_w+A_{t,st}}{A_p}[0.173\times10^{-8}(T_w^4-T_c^4)\times0.85] + \frac{A_p-A'_{st}}{A_p}I_o\,\bar{\alpha}_{c,s} + \frac{C(t_w-t_c)^{1/3}F(W_{s,w}-W_{s,c})(1040)}{(A_p/A_w)(0.24)} \quad (2c)$$

There are now three equations (1*b*), (2*c*), and (3*b*) containing three unknowns (t_w, t_c, and D) and sixteen constants or parameters. In Equation (1*b*) the only unknown is t_c, so its value can be determined directly. Then, since t_c is known, the only unknown in Equation (2*c*) is t_w, which

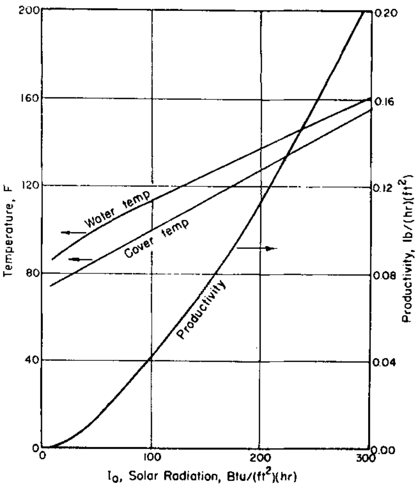

Fig. 5. Productivity, water temperature, and cover temperature vs. incident solar radiation on a horizontal surface.

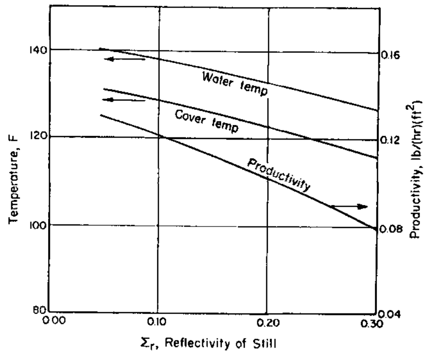

Fig. 6. Productivity, water temperature, and cover temperature vs. total effective reflectivity of distillation plant for solar radiation.

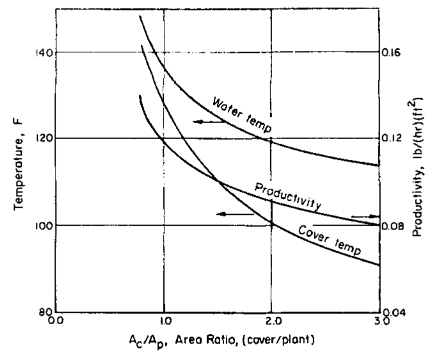

Fig. 7. Productivity, water temperature, and cover temperature vs. total surface area of cover divided by total plant area.

also can be determined directly because t_c is related to $W_{s,c}$ and t_w to $W_{s,w}$ by humidity tables and equations. Next, D can be found from Equation (3*b*), since t_w and t_c are known.

In Equations (2*c*) and (3*b*) there are three variables which were not directly obtainable from data on the stills at the Florida station, C, F, and K.

It is assumed that the evaporation rate from the distillate troughs is approximately that from an equal area of the basin. Therefore the amount of re-evaporated distillate would be proportional to the ratio of the distillate trough area to the basin area. This would normally be about 0.02. Consequently a constant value of 0.02 was used for K when these equations were developed. It was found that even if K were as large as 0.10, the results would be only slightly affected.

To determine values of C and F, representing pilot-plant operation, the values of all other variables obtained from the energy-balance measurements were inserted in Equations (2*c*) and (3*b*). These equations were then solved simultaneously for C and F. In the range of conditions experimentally encountered the value of F was found to be approximately constant at 0.255. The degree of approach to complete equilibrium between the circulating air and the two liquid surfaces was thus found to be reasonably independent of temperature over this operating range. Over wider ranges however this factor would be expected to vary. The value of C was found to be variable, indicating a dependence of h_i on t_w greater than that in normal free convection between dry surfaces. This result is due to the additional buoyant effect of moisture entering the air at the salt water surface and the greater circulation rate resulting from the lower mean density of the humidified air. It would be expected that C depends on the salt water temperature, and therefore an empirical relationship between C and t_w was established:

$$C = 0.0372\, t_w - 3.273$$

It was also necessary to establish a mathematical relationship for W as a function of t for the computer work:

$$W = \frac{H_r(0.6207)\,(10^{7.5627})\,(10^{-4077/t+460})}{29.92 - (H_r)\,(10^{7.5627})\,(10^{-4077/t+460})}$$

where H_r is 100% in this case.

In the computation of distiller performance, that is determination of t_w, t_c, and D over ranges of all parameters, a representative or normal value was first chosen for each variable. Then when the values of t_w, t_c, and D were computed by simultaneous solution of Equations (1*b*), (2*c*), and (3*b*), all but one of the variables were held at their representative values, while the particular parameter of interest was varied. Table 2 indicates the variables and the ranges of values as they were used in a program on an IBM-650 digital computer. The normal or representative value of each parameter is also listed. In addition the table contains a list of the constant factors used in the analysis and the values of substituted terms in the equations.

Computer Results

The principal results of the computations are presented in the graphs, Figures 5 through 13, in which saline-water temperature, cover temperature, and hourly distillation rate are correlated with each of eleven design and operating variables. The graphs cover ranges of variables shown in Table 2 for which the results appear reasonable. They represent instantaneous steady state values, involving no thermal lag (zero heat capacity) in the still.

Nearly all the correlations show that the productivity and the temperature of the saline water and of the cover are affected in the same direction by a change in a design or operating variable. Also the higher distillation rates are accompanied by a decrease in the difference between saline-water and cover temperature.

Figure 5 shows clearly the influence of solar radiation input on these factors. It is also evident that there is a threshold level of solar radiation for still operation, equivalent roughly to

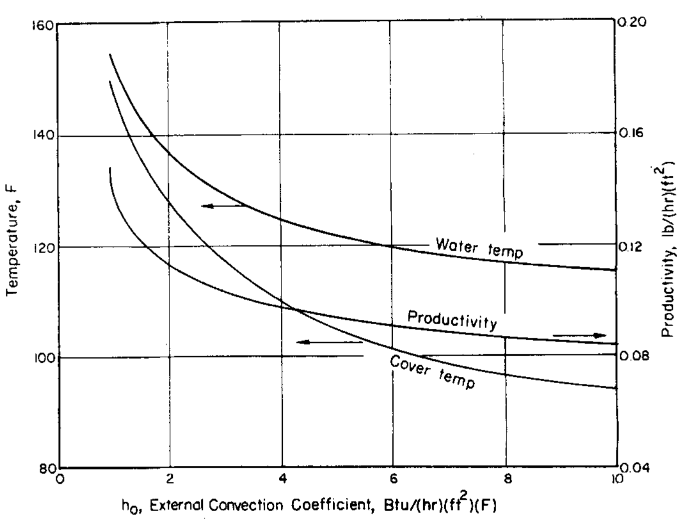

Fig. 8. Productivity, water temperature, and cover temperature vs. convection heat transfer coefficient between cover and atmosphere.

TABLE 2. VALUES OF PARAMETERS USED IN COMPUTER ANALYSIS

Variable	Range	Standard value
Variables		
I_o	10-350	200
Σ_r	0.05-.30	0.10
A_c/A_p	0.8-3.0	1.0
h_o	1.0-10.0	2.0
t_a	50-110	80
F	0.1-0.7	0.225 (pilot plant)
K	0-0.50	0.02 (pilot plant)
f, ratio T_s/T_a	0.86-1.0	0.95
$\alpha_{c,s}$	0.01-0.6	0.04
A'_{st}/A_p	0-0.15	0.10
$(A_w + A_{i,st})/A_p$	0.9-1.1	1.0
Constants		
ϵ_o		0.94 (glass)
ϵ_w		0.96
Tr_c		0 (glass)
$\Delta\Sigma H_p$		0
F_{wc}		0.85
$H_{v,t_v} - H_{d,t_d}$		1,040
A_p/A_w		1.205 (pilot plant)
All leakage		0
Heat loss to ground		0
Sensible heat change in distillate, brine, feed		0

Miscellaneous energy balance terms

Heat loss from external structures:

$$A_{st}/A_p[h_o(t_{st} - t_a) + 0.173 \times 10^{-8}(T_{st}^4 - T_s^4)\bar{\epsilon}_{st}] = 0.50\, I_o\, A'_{st}/A_p$$

Internal convection coefficient: $h_i = (0.0372\, t_w - 3.273)(t_w - t_c)^{1/3}$

Algebraic relationship for absolute humidity of saturated air:

$$W = \frac{H_r(0.6207)(10^{7.5627})(10^{-4077/t+460})}{29.92 - (H_r)(10^{7.5627})(10^{-4077/t+460})}$$

sensible heat requirements, and a steeply rising productivity rate at higher solar radiation levels. Curvature upward is observed up to a radiation level corresponding to approximately noon values on a clear day, above which a slight reversed curvature occurs. This is perhaps due to the increased importance of radiation heat transfer at the higher temperatures.

Figure 6 shows that at high total reflectivity of the still, yield is adversely affected and operating temperatures are low. Design and materials of construction, as well as varying solar incidence angles, are important in minimizing total effective reflectivity.

A pronounced effect of A_c/A_p is observed in Figure 7. The abscissa is proportional to A_c/A_w. At high values, that is for steeply sloping covers, temperatures and yields are low. If the cover is nearly flat, so that cover and water areas are nearly equal, productivity is much improved. A steep rise below $A_c/A_p = 1.0$ (which corresponds to $A_c/A_w = 1.2$ in the pilot plant) may be utilized by designing for an absolute minimum cover slope and cover-to-water ratio. Former experimental units with 45- and 60-deg. sloping covers are clearly less efficient than those with nearly flat covers.

Figures 8 and 9 show that atmospheric variables, such as wind (which affects h_o) and temperature, have similar effects on yield by influencing still temperatures. Thus low wind velocities, corresponding to low external coefficient, and high atmospheric temperature both lead to the high cover temperatures necessary for heat dissipation. This in turn raises the basin water temperature and distillation rate. A 25% improvement in yield is realized with an air temperature increase from 60° to 90°F. To secure large benefits from decreased h_o however wind velocities would have to be uncommonly low, below 3 mi./hr. The substantial improvements possible from both these factors suggest the use of double transparent covers, the lower cover serving as a condenser and the upper one providing a dead air space for inducing higher operating temperatures and yields. The merits of this step will depend on the relative cost of the additional cover and the value of the increased yield.

The degree of approach to thermal and humidity equilibrium in the solar still is shown in Figure 10 to have an important influence on performance. At the experimentally determined value of $F = 0.255$ only one-fourth of the theoretically transferable water is being recovered per unit of air circulated. That is four times as much air is wastefully transferring heat from basin to cover as theoretically necessary. Doubling F will increase yield by almost one-fifth. Means for achieving a closer approach to equilibrium are clearly desirable.

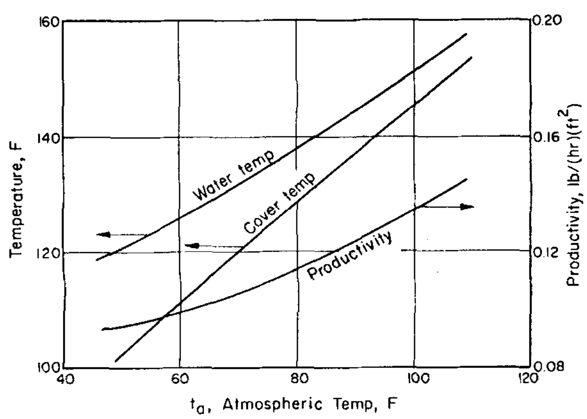

Fig. 9. Productivity, water temperature, and cover temperature vs. atmospheric sensible temperature.

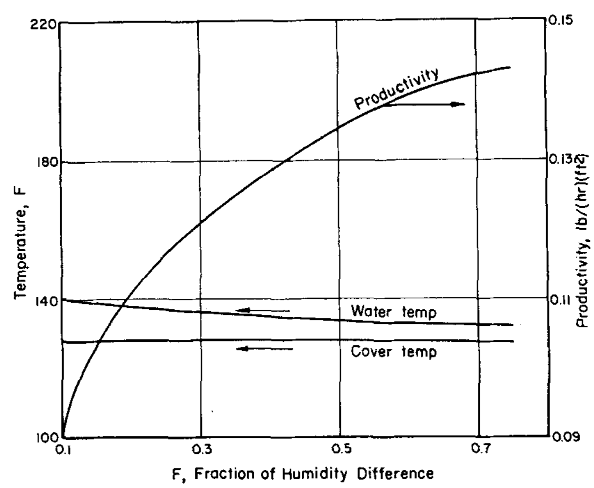

Fig. 10. Productivity, water temperature, and cover temperature vs. fraction of the limiting absolute humidity difference.

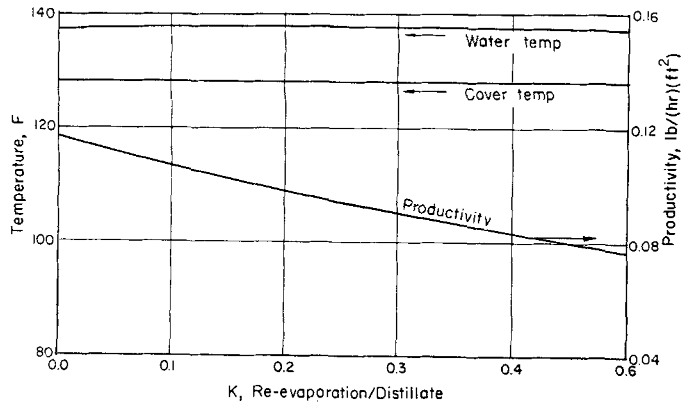

Fig. 11. Productivity, water temperature, and cover temperature vs. ratio of re-evaporation plus reflux to distillate yield.

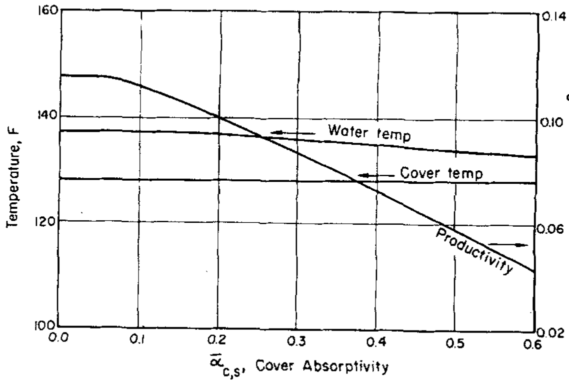

Fig. 13. Productivity, water temperature, and cover temperature vs. average effective absorptivity of cover for solar radiation.

Figure 11 shows the decrease in yield with increase in distillate loss through re-evaporation or reflux. Minimizing these effects by use of condensate troughs having small cross section and by avoidance of dripping from poorly wetted covers or internal structures is desirable.

The influence of effective sky temperature for radiation transfer is shown in Figure 12. At low values of f, corresponding to low atmospheric humidity and low effective sky temperature, the still operates at comparatively low temperature and efficiency. The effect of f on productivity is not large and generally is not controllable, although if a cheap cover surface of low emissivity could be developed, its use would increase yield considerably. Also, as indicated in connection with wind and ambient temperature effects, an additional transparent cover should improve performance.

Figure 13 shows that there is virtually no influence of cover absorptivity (for solar radiation) on productivity for the normal range of cover absorptivities between 0.01 and 0.06. This means that there would be little difference in performance between a perfectly clear glass or plastic film and a fairly low quality covering material. Apparently the absorption of this small amount of radiation on the cover, with its effect of increasing still temperature, largely offsets the reduction of energy received by the saline water. It is of interest that at values of $\bar{\alpha}_{c,s}$ above 0.06 the effect of this variable is to reduce the productivity progressively and to cause the water temperature to approach the cover temperature.

Exceedingly little effect on productivity or on water and cover temperatures was shown by the structural components of the still plant $\left(\frac{A_w + A_{t,st}}{A_p}\right.$ and $\left.\frac{A_{st}}{A_p}\right)$. Accordingly plots of these results are not presented.

CONCLUSIONS

The performance of basin types of solar stills under varying atmospheric conditions and operating methods and with various design features may be appraised by the solution of theoretical energy-balance equations. Because even the simplified equations involve more than a dozen variables analysis by digital computer methods is practically required. Determination of the ranges and representative values of most of the parameters is facilitated by use of pilot-plant data.

Results of the computer analysis, in the form of graphical relationships between hourly distillation rate, basin temperature, cover temperature, and eleven design and operating variables, show the following principal effects.

(1) High distillation rates are accompanied by high temperatures of the still and by relatively small temperature differences between the basin and the cover.

(2) Distillation rate increases with increase in solar radiation, atmospheric temperature, and degree of approach to humidity equilibrium in the distiller. Productivity and temperatures increase with decrease in wind velocity (external coefficient of heat transfer), reflectivity of the system, ratio of cover area to water area, and re-evaporation and reflux of condensate.

(3) The effects of moderate changes in the size of structural components and the transmissivity of the cover for solar radiation are small.

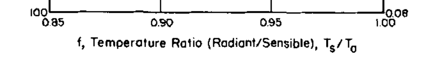

Fig. 12. Productivity, water temperature, and cover temperature vs. atmospheric effective radiant temperature divided by sensible temperature of atmosphere.

These generalizations indicate the desirability of maximizing the operating temperatures in a solar distiller by all practical means. A number of other measures would also contribute to increased distiller yield. These include reducing the long-wave emissivity of the covering surface, the use of double transparent covers with a dead air space between them, screening of the distiller for high winds, the use of the flatest practical cover thus keeping at a minimum the area of reflecting surfaces, the use of low reflectivity covering material (for solar radiation), the use of designs contributing to the closest possible approach to vapor-liquid equilibrium at the two liquid surfaces, and of course locating the plant in a hot, sunny climate. To what extent these measures can be justified will depend on the cost of incorporating each in comparison with the value of the increased yield. Further study of these relationships is indicated.

It should be remembered that the computer was based on an assumption of zero distiller heat capacity and steady state conditions of operation. This situation is approached in practice to various degrees, depending on the distiller design and the climatic factors. A more nearly complete appraisal of the performance of a specific design of solar still requires solution of the energy-balance equations with the thermal storage term retained. Hour-by-hour computation, under typical solar and atmospheric conditions (when one takes into consideration the thermal capacity of the basin water, plant structure, and underlying ground), may then be employed in a determination of productivity throughout several representative days. In a deep-basin design distillate output occurs continuously, whereas in a low thermal capacity distiller operation ceases at night. By means of such analyses determination of the effects of water depth should be readily obtainable, whereas this parameter is difficult to evaluate experimentally because of the need for averaging data over weeks or months of operation. Evaluation of this design variable and other solar distiller refinements should be undertaken in further computer studies.

NOTATION

A = basin area
A_c = total surface area of transparent cover, sq. ft.
$A_{i,st}$ = surface area of structures above water and below cover, sq. ft.
A_p = total horizontal area of distiller plant, comprising area of water surface and ground area of structures, sq. ft.
A_{st} = total exposed surface of plant minus area of transparent covers, sq. ft.
A'_{st} = horizontal projected area of exposed portions of plant other than glass surface, sq. ft.
A_w = area of water surface, sq. ft.
B = brine production rate, lb./(hr.) (sq. ft. plant)
C = parameter in equation, $h_i = C(t_w - t_c)^{1/3}$, B.t.u./(hr.) (sq. ft.) $(F^{4/3})$
C_{p_a} = heat capacity of dry air, B.t.u./(lb.)(°F.)
D = net distilled water production rate, lb./(hr.) (sq. ft. plant)
d = distilled water re-evaporated from collection channels, lb./(hr.) (sq. ft. of plant)
F = fraction of the limiting absolute humidity difference in the distiller enclosure which is actually achieved in operation, dimensionless
f = T_s/T_a, dimensionless
H_{b,t_b} = enthalpy of brine leaving plant, B.t.u./lb.
H_{d,t_d} = enthalpy of distillate at mean temperature leaving lower edge of cover, B.t.u./lb.
$H_{d,t_d'}$ = enthalpy of distillate at mean temperature of distillate leakage, B.t.u./lb.
H_{d,t_p} = enthalpy of distillate leaving plant, B.t.u./lb.
h_i = coefficient of heat transfer by convection from water surface to lower side of cover, B.t.u./(hr.) (sq. ft. of water surface) (°F. temperature difference between water surface and cover surface)
h'_i = coefficient of heat transfer by convection from structures above water and below cover to cover, B.t.u./(hr.) (sq. ft. of such structural area) (°F. mean temperature difference between such structures and cover).
h_o = coefficient of heat transfer by convection from transparent cover to atmosphere, B.t.u./(hr.) (sq. ft cover) (°F. temperature difference between cover and air.
H_r = relative humidity
H_{sw,t_o} = enthalpy entering sea water at t_o F, B.t.u./lb.
H_{v,t_v} = enthalpy of water vapor at mean temperature of vapor reaching cover, B.t.u./lb.
$H_{v,t'}$ = enthalpy of water vapor at mean temperature of vapor leakage, B.t.u./lb.
I_o = solar radiation incident on horizontal surface, B.t.u./(hr.) (sq. ft) of gross distiller plant area
k = thermal conductivity of the air, B.t.u./(hr.) (ft.) (°F.)
K = ratio of re-evaporation plus reflux, to distillate yield, dimensionless
$\overline{k/l}$ = effective coefficient of heat transfer by conduction from salt water through basin bottom and ground, B.t.u./(hr.) (sq. ft. plant)
L = length of one side of basin
L_a = leakage loss of air to atmosphere, with specific heat C_{p_a}, at temperature t'_v, lb./(hr.) (sq. ft. plant)
L_b = leakage loss of brine at t'_b F, lb./(hr.) (sq. ft. plant)
L_d = leakage loss of distillate at t'_d F, other than by return flow into brine, lb./(hr.) (sq. ft. plant)
L_v = leakage loss of vapor to atmosphere, with enthalpy H_{v,t'_v} at t'_v F, lb./(hr.) (sq. ft. plant)
M_a/M_{H_2O} = pounds of dry air circulating between water surface and lower side of cover, per pound of water condensed on cover, lb. air/lb. water
P_w = water vapor pressure, in. Hg
q_{st-c} = heat transfer by conduction from structures to cover, B.t.u./(hr.) (sq. ft. plant)
r = distilled water dripping from cover into basin, lb./(hr.) (sq. ft. of plant)
R = thermal radiation, B.t.u./(hr.) (sq. ft.)
t_a, T_a = temperature of atmosphere, °F, °R.
t_{a_1} = mean temperature of air approaching cover, °F.
t_{a_2} = mean temperature of air approaching water surface, °F.
t_b = temperature of brine leaving plant, °F.
t_c, T_c = temperature of transparent cover, °F, °R.
t_d = temperature of distillate leaving lower edge of cover, °F.
t_{gr} = effective temperature of ground, °F.
$\bar{t}_{i,st}, \bar{T}_{i,st}$ = mean temperature of structures above water and below cover, °F., °R.
t_p = temperature of distillate leaving plant, °F.
T_s = effective temperature of the atmosphere for exchange of radiation, °R.
t_{st}, T_{st} = temperature of covering structures, °F., °R.
t_w, T_w = temperature of water in basin, °F., °R.
Tr_c = transmittance of cover for radiation emitted at t_w, dimensionless
V' = wind velocity, ft./sec.
$W_{s,c}$ = absolute humidity of air saturated with water vapor at t_c, lb. water/ lb. air
$W_{s,w}$ = absolute humidity of air saturated with water vapor at t_w, lb. water/lb. air

Greek Letters

$\bar{\alpha}_{c,s}$ = effective absorptivity of cover for solar radiation, averaged over appropriate angles of incidence, dimensionless
ϵ_o = emissivity of cover at t_c, dimensionless
ϵ_{st} = emissivity of internal still structures at $\bar{t}_{i,st}$, dimensionless
$\bar{\epsilon}_{st}$ = average effective emissivity of covering structures, dimensionless
ϵ_w = emissivity of water at t_w, dimensionless
$\Delta\Sigma H_p$ = change in energy content of water and structures, B.t.u./hr.
$F_{i,st-c}$ = over-all interchange factor for radiation from structures to cover, based on area of structures above water and below cover, dimensionless
F_{wc} = over-all interchange factor for radiation from water to cover, based on water area, dimensionless
σ = Stefan-Boltzman constant, B.t.u./(hr.) (sq. ft.) $(°R.)^4$
Σr = total effective reflectivity of distiller plant for solar radiation, including reflection from cover surfaces, water surfaces, basin bottom, and supporting structures above

and below cover, dimensionless

LITERATURE CITED

1. Bloemer, J. W., R. A. Collins, and J. A. Eibling, "Saline Water Conversion," Am. Chem. Soc., Advances in Chemistry Series, No. 27 (1960).
2. Harding, J., *Proc. Inst. Civil Engrs.*, 73, p. 284 (1883).
3. Jakob, Max, "Heat Transfer," Vol. I, p. 536, Wiley, New York (1949).
4. Keller, J. D., *Trans. Am. Soc. Mech. Engrs.*, **49-50**, Part II, pp. 735-748 (1927-8).
5. Löf, G.O.G., *Office of Saline Water Research and Development Progress Report No. 4* (August, 1954). Available from Office of Technical Services, Washington, D. C., PB 161378.
6. McAdams, W. H., "Heat Transmission," 3 ed., p. 249, McGraw-Hill, New York (1954).
7. *Ibid.*, p. 69.
8. Parmalee, G. U., and W. W. Aubele, *Heating, Piping, and Air Conditioning*, **23**, pp. 120-129 (November, 1951).
9. Strobel, J. J., et al., "Proceedings of the Symposium on Saline Water Conversion, 1957," National Academy of Sciences, Publication No. 568 (1958).
10. Bloemer, J. W., R. A. Collins, and J. A. Eibling, "Two Year Progress Report on the Study and Field Evaluation of Solar Sea Water Stills" (1961). Available from the Office of Saline Water, Washington 25, D. C.

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APPENDIX

Commentary on Terms Used in Computing Energy Balances

(1) The effective atmospheric temperature for radiation is not far below T_a, especially at sea level. However a correction can be made for somewhat better accuracy. Parmalee and Aubele (*8*) show radiation from a clear sky can be represented by $R = \sigma T_a^4 (0.55 + 0.33 \sqrt{P_w})$. The expression can be used for computing the effective space temperature by defining T_s as $\sqrt[4]{T_a^4 (0.55 + 0.33 \sqrt{P_w})}$. If a correction factor f is used in $fT_a = T_s$, then $f = \sqrt[4]{0.55 + 0.33 \sqrt{P_w}}$. If $P_w = 0$, $f = 0.86$, and if the temperature and humidity are 100°F. and 90% respectively, $P_w = 1.8$ in. and $f = 0.998$.

(2) The convective heat transfer coefficient inside the distiller is calculated by assuming free convection between two horizontal parallel surfaces and applying a suitable correction factor for the presence of wetted areas. In accordance with the data of Mull and Reiher and Jakob's equations based on these data (*3*), when the modified Grashof number N_{Gr} is above approximately 4×10^5, the data can be correlated by the equation $h_i/k = 0.068 (N_{Gr})^{1/3}$. Above a certain distance between the plates this equation reduces to $h_i = 0.275 (t_1 - t_2)^{1/3}$, which is the relation for free convection from a single upward-facing horizontal plate. Substitution of appropriate values shows the Grashof number N_{Gr} to be about 10^8, and when the values are substituted in the enclosure equation above, the single-plate relationship is developed. Instead of the constant coefficient 0.275, a variable C is substituted, in recognition of the higher convection rate due to moisture addition to the air. C is a function of t_w, found experimentally to be $C = 0.0372\, t_w - 3.273$. Because $h_i = C (t_1 - t_2)^{1/3}$, $h_i (t_w - t_c) = C (t_w - t_c)^{4/3} = (0.0372\, t_w - 3.273)(t_w - t_c)^{4/3}$.

(3) Ideally, air circulating in the distiller is alternately heated and cooled between water temperature and cover temperature, and it remains saturated with water vapor at both temperatures. This is the limiting case, actual operation being less efficient. In the limiting case Equation (3) can be simplified to $\frac{A_p}{A_w} (D + L_d + d + r) = \frac{h_i}{C_{p_a}} (W_{s,w} - W_{s,c})$, where $W_{s,w}$ and $W_{s,c}$ are absolute humidity of air saturated with water vapor at the two temperatures. As an additional parameter let F be the fraction of the limiting humidity difference actually achieved in operation. Thus $\frac{A_p}{A_w} (D + L_d + d + r) = \frac{h_i}{C_{p_a}} F (W_{s,w} - W_{s,c})$, where $C_{p_a} = 0.24$ B.t.u./(lb.)(°F.) for air. Values of the parameter F can then be chosen, although without data their probable values can only be conjectured. For example if water and cover temperatures are 130° and 100°F., respectively, the two absolute humidities at saturation are 0.11 and 0.043. Hence the maximum water transfer per pound of air circulated is 0.11 — 0.043 = 0.067 lb. But if the actual air-vapor conditions are 125°F., 90% relative humidity and 105°F., saturated, the humidity difference is 0.086 — 0.051 = 0.035. This is only half as much water transferred per pound of air circulated.

(4) The coefficient for external convective heat transfer is $h_o = a + b(V')^n$, where for wind velocities below 16 ft./sec. and smooth surfaces $a = 0.99$, $b = 0.21$, and $n = 1.0$ For wind velocities between 16 and 100 ft./sec. $a = 0$, $b = 0.50$, and $n = 0.78$ (*6*). Hence in low range $h_o = 0.99 + 0.21\, V'$, and in high range $h_o = 0.5(V')^{0.78}$.

(5) The value of A_{st}/A_p should be very small in a well-designed solar distillation plant. It represents the portion of the plant area covered by structural components other than glass. Except for very minor contributions to effective distiller heat input by conduction to the interior of the still from the solar-exposed surfaces (and corresponding conduction losses in sunless periods of operation), the total convection and radiation to the atmosphere from these surfaces equals the solar radiation intercepted by them. It is therefore assumed that 90% of the solar energy absorbed by the exterior nonglazed surfaces will be transferred directly back to the atmosphere and 10% will be usefully conducted to the distiller. If the average absorptivity of these exterior surfaces is assumed to be 0.55, the entire term in Equation (1) containing A_{st}/A_p can be replaced by $0.55\, I_o \cdot 0.90 \cdot A'_{st}/A_p$, where A'_{st} is the horizontal projected area of all external, nonglazed areas. This reduces to approximately $0.50\, I_o A'_{st}/A_p$.

(6) For the term $H_{d,t_p} = 1.0 (t_p - 32)$, where no heat exchange between distillate and water supply is employed, $t_p = t_d = t_c$, and hence $H_{d,t_p} = t_c - 32$. Further, assume that $B = \frac{1}{2}D$; that is one third of feed is produced as brine, two-thirds as distillate. As approximation, C_p of brine $= C_p$ of 10% salt solution = approximately 0.9 B.t.u./(lb. of solution) (°F.). With no heat exchange provided $t_b = t_w$ and $BH_{b,t_b} = \frac{1}{2} D \times 0.9 (t_w - 32) = 0.45D (t_w - 32)$.

(7) If the leakage of brine, distillate, vapor, and air are negligible, then $L_B = 0$, $L_D = 0$, $L_A = 0$, and $(D + B)(H_{sw,t_o})$

$$= (D + \frac{D}{2} \times 0.97 (t_o - 32) = 1.46\, D$$

$(t_o - 32)$, where 0.97 = specific heat of sea water. For the design study the sea water inlet temperature is taken at 70°F.; hence its energy supply is $1.46\, D (70 - 32) = 55.5D$.

(8) The term $\frac{\bar{k}}{l} (t_w - t_{gr})$ represents the conduction loss to the ground. Because this is an uncertain quantity and the respective temperatures, conductivities, and path lengths are not readily evaluated, it is desirable to substitute the equation of Keller (*4*) whence the heat loss $= \frac{SkA}{L} (t_w - t_a)$, where $S = 4.4$ for a square basin and k = conductivity of soil (assumed to be 0.5). Then, $\frac{\bar{k}}{l} (t_w - t_{gr}) = 4.4 \times 0.5 \times \frac{1}{L} (t_w - \bar{t}_a)$, where $\bar{t}_a$ = mean atmospheric temperature and the loss is on a basis of 1 sq ft. When one assumes $\bar{t}_a = 75$ F, $\frac{\bar{k}}{l} (t_w - t_{gr}) = \frac{2.2}{\sqrt{A_p}} (t_w - 75)$, assuming that the plant is square.

(9) The transmissivity of cover and condensate film Tr_c for thermal radiation at 100° to 150°F. is zero for glass but may be higher for certain plastic films, particularly if they are only partially wetted by condensate drops. A continuous water film only 0.03 mm. thick will transmit only about 8% of the radiation from a 135°F. black body source. A film 0.01 mm. will transmit about 25%. Hence if the plastic film is wettable and if it is also partly transmissive in the same wave length ranges as water, some of the thermal radiation from the water will be transmitted by the cover system. In this present analysis transmissivity of glass is used; that is $Tr_c = 0$. From McAdams (*7*) $F_{wc} = 0.85$, based on the assumption that the cover is completely wetted by a water film above 0.05 mm. thickness.