

Factors Determining the Rate of Solar Evaporation in the Production of Salt

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ABSTRACT

Salt has been made by solar evaporation for thousands of years, but the evaporation process has become properly understood only during this century.

The theoretical basis of the natural evaporation process evolved from the sink strength theory through the energy balance theory of the classical Penman-Ferguson combined sink strength-energy balance theory in which evaporation is determined from four meteorological parameters -- net gain of radiant energy, air temperature, humidity and wind.

Under given meteorological conditions the evaporation rate of brines falls off with increasing salinity. This is caused by lowered vapour pressure, and it involves higher brine temperature -- as the theory requires.

This theory, developed for an evaporating surface of small extent and for steady values of the parameters, can be applied to a larger area with fluctuating parameters, provided that the pond is shallow, that the parameters are averaged over several days, and that the appropriate empirical sink strength formula is used in the combined equation.

Reconciliation of the theory with actual saltfield conditions is satisfactory where the brine is unsaturated, but after the Salting Point the conditions may deviate from the ideal owing to loss of radiant energy by reflection. This can be largely corrected by the addition of a suitable dye to the brine.

The theory is tested in some experimental work carried out by the author on both the small and the large scale. Agreement is good at low salinities, but there is significant divergence at high salinities. Some interesting derivations of the theory are also tested experimentally.

INTRODUCTION

Solar evaporation of brines in shallow ponds in the present context is a particular case of natural evaporation from a free water surface. Liquid water is able to gain sufficient energy, under appropriate conditions, to change into the vapour state and to dissipate into the atmosphere. Doing this with any rapidity calls for a substantial supply of energy which is usually derived from solar radiation -- hence the prefix "solar."

Anticipating some conclusions, the facts are that evaporation rate per unit area falls off as the size of the evaporating body increases, and that (in the case of saline waters) evaporation rate falls off as the salinity increases. Pond depth variation has little effect. The salinity effect is due to the lowering of the water vapour pressure by the dissolved solids. The evaporation process is controlled by its energy balance (see Bonython, 1956); the lowering of vapour pressure by salinity may be considered to start off by permitting less energy to escape as latent heat of vaporization -- owing to the reduced driving force in the mass transfer phase -- so causing build-up of sensible

heat, or a temperature rise. In being warmer, the saline water will fare adversely in the exchange of sensible heat and long-wave radiation between its surface and the atmosphere. The resultant shift in the energy balance towards greater losses (or lesser gains), and towards less efficient conversion of available energy into latent heat, finally makes the rate of evaporation of a saline water lower than that of fresh, or of a less saline, water exposed to the same meteorological conditions.

The process of natural evaporation in its general form operates all over the globe from oceans, lakes, rivers, small pools, and a variety of other surfaces (including snow and ice); it is an essential part of the hydrologic cycle (Thornthwaite, 1937). This paper deals with its particular application to the concentration of sea water and other brines to produce common salt and other salts.

Historically the use of solar evaporation for saltmaking is very old, being referred to, for instance, by the Chinese before 2200 B.C. (Baas-Becking, 1931). The controlling factors were then only dimly understood, wind being considered a dominant one. Proper understanding was long in coming, and was little further advanced in 1669 when a report referring to saltmaking on the island of Rhé (Baas-Becking, 1931) said:

" 'tis obvious that the hottest years make the most salt; where yet it is to be noted, that besides the heat of the sun the Winds contribute much to it, in regard that less salt is made in Calme than in Windy weather."

While the 19th Century saw the unravelling of the chemistry of the salts deposited when sea water is evaporated, researchers into natural evaporation made relatively little advance. Most progress had to wait until the present Century. A review of the progressive development of the physical theory of evaporation which eventually took place will convey an appreciation of the factors now known to control it.

DEVELOPMENT OF EVAPORATION THEORY

There were found to be empirical relationships between evaporation rate (measured in evaporimeters, pans, ponds, etc.) and the meteorological parameters wind and humidity. They were shown to be dependent on the difference between the pressure of water vapour at the water surface and in the air above, together with an atmospheric turbulence factor closely related to wind speed affecting the air layer through which the water vapour was passing. It could be expressed in an equation of mass transfer termed the Dalton equation (Dalton, 1802), which may be written:

$$E = f(u)(p_w - p_a) \dots\dots\dots (1)$$

where E = evaporation rate

$f(u)$ = a function of the horizontal wind speed

p_w = vapour pressure of the water surface

p_a = partial pressure of water vapour in the air

or in another form:

$$E = k (p_w - p_a) \dots\dots\dots (2)$$

where k = coefficient of mass transfer from water to air

Barometric pressure was another factor recognized (Rohwer, 1931) as influencing evaporation rate. Later work (Millar, 1932), (Hickox, 1946) suggests that E is inversely proportional to the 0.25 power of P , total barometric pressure.

The importance of surface temperature in determining water vapour pressure was hence understood, but the factors that in turn controlled the temperature were not understood. The volume of work done during the late 19th Century and early 20th Century was enormous, the investigators including Symons (1863), Fitzgerald (1886), Bigelow (1907), and Meyer (1915).

The importance of the energy balance in evaporation was probably first recognized by Ångström (Ångström, 1920), and then during the 1920's the theory was developed by Bowen, Cummings, Richardson, et al. (Bowen, 1926), (Cummings & Richardson, 1927). The first form of the energy balance equation (as applied to lakes) was:

$$E = \frac{I - B - S - K - C}{L} \dots \dots \dots (3)$$

where E = rate of evaporation

I = incoming radiation (short- and long-wave)

B = back radiation to the sky (long-wave)

S = change of heat stored in the water

K = heat interchange between air and water

C = combined correction factor for leakage, expansion, etc.

L = latent heat of vaporization of water

It was later modified to:

$$E = \frac{I - B - S - C}{L (1 + \beta)} \dots \dots \dots (4)$$

where β = the Bowen ratio

The Bowen ratio was a relation that Bowen had noted between the amount of energy passing out as latent heat of vaporization and that passing between the air and the water as sensible heat. It can be expressed as:

$$\beta = 0.46 \frac{\theta_w - \theta_a}{p_w - p_a}$$

where θ_w = water temperature, deg. C

θ_a = air temperature, deg. C

and p_w and p_a are in mm. of mercury

It had been discovered empirically, and the fact that it had a basis in theory (see Ferguson, 1952) was not clear at the time.

Two incomplete evaporation concepts had therefore been developed by the 1930's:

1. The mass transfer (Dalton) concept, which showed the dependence upon water temperature, air humidity, and atmospheric turbulence, but which was incomplete insofar as it gave no indication of the nature of the control of water temperature.
2. The energy balance concept, which showed the ultimate dependence upon energy supply, but which failed to specify (other than empirically) how energy would be apportioned between that used as latent heat of vaporization and that exchanged as sensible heat.

The problem of reconciling the two concepts and producing a single, comprehensive relationship was solved around 1950 by two independent researchers. H. L. Penman (Penman, 1948) and J. Ferguson (Ferguson, 1952), following different approaches, reached virtually the same goal in an expression of the combined mass transfer -- energy balance theory. Only four meteorological parameters, viz. net gain of radiant energy, air temperature, humidity and wind, are involved in the equation. The development of the equation will be set out in some detail subsequently.

TRANSFER PROCESSES OVER AN EVAPORATING SURFACE

There has been much investigation during the last three decades on the transfer of matter and heat in the lower layers of the atmosphere (see Priestley, 1959) and numerous "aerodynamic" equations have been elaborated. In the application to the case of evaporation, the air which is

moving across a pond is rarely isothermal, and it is also undergoing shear in that its horizontal velocity increases with height above the water surface -- usually exponentially. Escaping water vapour first passes by molecular diffusion through the laminar boundary layer of surface air (millimetres thick), and then by eddy diffusion through a very much deeper layer of overlying air. At a point on the water surface a short distance downwind from the leading edge of the pond the major part of the resistance to the escaping water vapour is due to the laminar layer, the water vapour being rapidly dispersed through the less resistant eddy diffusion layer. With increasing downwind distance the water vapour tends to build up above the pond, and a greater proportion of the resistance is shifted to the eddy diffusion layer. An increasing depth of the atmosphere hence becomes effectively involved in the transfer process. The extreme case is found over the oceans, where most of the resistance is offered by the eddy diffusion layer, now effectively thousands of feet deep. In the aerodynamic equations developed mainly for the latter situation account has to be taken of factors like the thermal stability of the atmosphere and the "hydrodynamic roughness" of the water surface. Similar considerations apply to the transfer of heat in the lower atmosphere.

It now remains to be ascertained whether and to what extent these extensions of transfer theory have to be taken into account in the evaporation from the comparatively limited surfaces of solar evaporation ponds. When in a transfer process there are two or more resistances in series, and one is distinctly larger than the others, that resistance is found virtually to "control" the process. With an evaporating surface of small downwind dimension -- a few feet, say -- the laminar layer will probably control; when the dimension is one of many miles the eddy diffusion layer is likely to control. Somewhere in between there will be a transition from one control to the other. The large-scale evaporation investigations at Lake Hefner, U. S. A. (where the downwind dimension is 12,000 feet) (3,700 m.) have shown (Marciano and Harbeck, 1952) that atmospheric water vapour content at 8 m. above the water is close to the upwind value, and that evaporation can be computed quite accurately by using values of the meteorological parameters measured at normal height upwind of the lake. These and other observations indicate that mass transfer in the evaporation process of a water body of this dimension can be described sufficiently accurately for practical purposes using a simple equation of the Dalton type and ignoring complications like atmospheric stability. Presumably the laminar layer is still controlling the process.

The downwind dimensions of ponds used in solar salting range from, say, 100 feet (30 m.) to 10,000 feet (3,000 m.) and so fall within the limits between which the simple transfer equations, such as Eqns. (1) or (2), can be used. The $f(u)$ of Eqn. (1) can be replaced by $c \cdot u$, where c is a factor related to both pond downwind dimension, D , and to the height, z , above the ground at which wind speed is measured, and u is mean wind speed. Figure 1 shows the change of c with D for wind speeds measured in m./sec. at $z = 10$ m. (or extrapolated to 10 m., using the "1/7 power law" of wind shear). It shows that after falling to a value of about 7.5×10^{-4} at

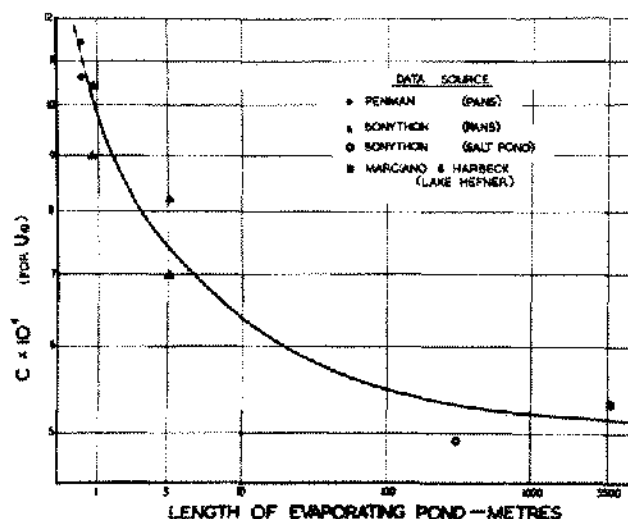


Figure 1. Effect of pond size on transfer coefficient.

D = 10 feet (3 m.) the rate of decrease of c becomes very much slower. In the dimension range 2 - 10 feet (0.6 - 3 m.) for pans, not only is c undergoing rapid change, but unpredictable effects, like the height and shape of the pan rim, play a part; this is only one of the problems associated with the use of small pans in evaporation investigations (Bonython, 1956), (Hounam, 1956), (Nimmo, 1964).

THE COMBINED MASS TRANSFER -- ENERGY BALANCE EQUATION

The Penman Equation:

This is written:

$$E = \frac{H \Delta + E_a \gamma}{\Delta + \gamma} \dots\dots\dots (5)$$

where E = rate of evaporation under the particular conditions

E_a = fictitious rate of evaporation assuming the water surface to be at air temperature

H = net gain of radiant energy

Δ = the slope of the vapour pressure vs. temperature curve at air temperature

γ = the constant of the wet-and-dry bulb hygrometer equation

First E_a must be derived from

$$E_a = (e_a - e_d) f(u) \dots\dots\dots (6)$$

where e_a = saturation water vapour pressure in the air at air temperature

e_d = saturation water vapour pressure in the air at the Dew Point

$f(u)$ = mass transfer coefficient for water vapour as a function of wind speed

Then it is inserted in Equn. (5). Apart from the physical constants the components in Equns. (5) and (6) consist of the four meteorological parameters -- net gain of radiant energy, air temperature, humidity and wind -- or are derivatives of them.

The Ferguson Equation:

In its simplest form it is:

$$E = \frac{2h}{L} \left\{ f' (Q/h + 2 p_a + e_a) - p_a \right\} \dots\dots\dots (7)$$

where Q = net gain of radiant energy

h = coefficient of heat transfer

f' = a function of the vapour pressure vs. temperature curve for water

and the other symbols are as already defined.

In its derivation Ferguson combined three expressions:

$$(1) \quad E = k (p_w - p_a) \dots\dots\dots \text{(which is Equn. 2)}$$

where k is the mass transfer coefficient already defined.

$$(2) \quad h/Lk = 0.50 \dots\dots\dots (8)$$

which is the interrelation between the coefficients of heat and mass transfer across a common interface.

$$(3) \quad Q = Lk (p_w - p_a) + h (\theta_w - \theta_a) \dots \dots \dots (9)$$

the basic energy balance equation, which can be rearranged as:

$$2 p_w + \theta_w = Q/h + 2 p_a + \theta_a \dots \dots \dots (10)$$

when k is replaced by its equivalent in terms of h in Equn. (8)

In the operation of combining the expressions the unknown parameters p_w and θ_w are removed by introducing the function, f' , which is actually the relationship between p_w and $(2 p_w + \theta_w)$ derived from the standard vapour pressure vs. temperature relationship.

h is used in the final equation in preference to k because of the more convenient value of the former in customary units.

Comparison and Consequences of the Equations

The Penman equation involves an assumption which can be a source of error under certain conditions -- that the value of Δ is constant over the range between air and water temperature. Since Δ changes in value by 30% between 20° and 25°C. it is clear that the assumption is not warranted when $(\theta_w - \theta_a)$ is appreciable.

The temperature of evaporating fresh water is usually not very different from that of the air above, but with some lakes in dry, inland surroundings -- like Lake Mead, U. S. A. -- the air may be considerably warmer (Harbeck, 1958). Conversely, in the case of strong brines evaporating in normal environments, the brine temperature is likely to be several degrees above that of the air. The objection concerning Δ holds in these cases, and for this reason the Ferguson equation is to be preferred for describing the evaporation of brines in solar salting. (It will be shown that, in the case of highly saline brines, yet another refinement of the equation is required.)

The combined mass transfer-energy balance equation was derived on the basis of small evaporating areas of shallow depth. Ferguson (Ferguson, 1952), investigated the problem thoroughly by inserting fluctuating values of the meteorological parameters and also heat storage terms, into simultaneous equations fed into and solved by the differential analyzer. He showed that the use of mean values of the parameters, and the neglect of heat storage, was valid provided that the period of time taken was long enough -- say, three days or more, and that the pond was shallow -- say, no more than two feet or so deep.

A question of considerable interest is the effect of changes in the individual parameters upon the resultant evaporation.

Ferguson (unpublished) applied partial differentiation to Equn. (7) and obtained these results:

$$\frac{\delta E}{\delta Q} = \frac{0.68}{L} = 0.00117 \text{ cm. /cal.}$$

$$\frac{\delta E}{\delta \theta_a} = \frac{0.68 h}{L} = 0.00116 h \text{ cm. /hr. /}^\circ\text{C.}$$

$$\frac{\delta E}{\delta p_a} = \frac{0.64 h}{L} = -0.0011 h \text{ cm. /hr. /mm. of mercury}$$

$$\frac{\delta E}{\delta h} = \frac{1}{L} (0.68\theta_a - 0.64 p_a - 0.9) \text{ cm. /cal. /}^\circ\text{C.}$$

The results apply to a water temperature in the general vicinity of 20°C. The result for change of evaporation with wind is the most complicated; under certain conditions (low temperature and high humidity) an increase of wind can actually decrease evaporation.

An example of the effect on evaporation of changes in the parameters is given when, taking the mean meteorological conditions at three widely divergent Australian localities in the summer month of January, each parameter is varied in turn by 10% of its value. The effect of these changes on evaporation rate itself is shown in Table 1.

TABLE 1
Effect of Varying Parameters Separately

| Locality | Values of Parameters | Effect on Evaporation of 10% Variation in Parameter |
|------------------------------|----------------------------------------|-----------------------------------------------------------|
| Dry Creek (near Adelaide) | Q_a 23.0 cal./cm. ² /hr. | 8% |
| | θ_a 21.7°C. | 5% |
| | p_a 9.3 mm. of merc. | 2% |
| | h 0.7 cal./cm. ² /hr./°C. | 3% |
| Darwin | Q_a 17.0 cal./cm. ² /hr. | 10% |
| | θ_a 28.7°C. | 8% |
| | p_a 23.5 mm. of merc. | 6% |
| | h 0.5 cal./cm. ² /hr./°C. | 1% |
| Hobart | Q_a 18.5 cal./cm. ² /hr. | 9% |
| | θ_a 16.1°C. | 5% |
| | p_a 8.0 mm. of merc. | 3% |
| | h 0.7 cal./cm. ² /hr./°C. | 2% |

h has been computed for $c = 5.5 \times 10^{-4}$.

Radiant energy is clearly the dominant factor, followed by air temperature. The least important is humidity or wind -- depending upon whether the climate is dry or humid.

In practice, and in the short term, the effect of a change of wind speed may seem to have a striking effect, but this is transitory, for the compensating effect of the energy balance mechanism soon modifies the longer term result. Wind -- consider $f(u)$ of Equn. (1) -- was long loosely supposed to be the controlling factor in the evaporation process, but it is not, because p_w can vary in a way that can nullify the effect of wind.

Ferguson (1952) has shown that the varying of pond depth has only a minor effect upon evaporation -- always assuming that there is complete absorption of solar radiation entering the water. As compared with a pond of depth six inches (15 cm.), a shallow one of, say, one inch (2.5 cm.) will have an evaporation rate approximately 4% greater, and a deep one of, say, 40 inches (100 cm.) will have an evaporation rate approximately 4% less, under the climatic conditions defined in Table 1 for Dry Creek, South Australia. Over the depth range current in solar salt practice the evaporation variation is theoretically only about half this, and because under field conditions imperfect absorption of solar radiation in the shallower range is likely to frustrate the attainment of the full evaporation theoretically possible there, the variation of evaporation with depth can be virtually neglected. This conclusion has support on both theoretical and experimental grounds (Bloch, Farkas, and Spiegler, 1951).

THE THEORY APPLIED TO THE EVAPORATION OF SALINE WATERS

Theoretical consideration of the aspects of the problem of the evaporation of saline waters has been given by other authors (Bloch, Farkas, and Spiegler, 1951), (Ferguson, 1952), (Harbeck, 1955).

The Ferguson equation in the form of Equation (7) is readily adapted for use with brines whose vapour pressure differs from that of water by using a set of values of the function f' obtained from the relevant vapour pressure vs. temperature data. It involves preparing a set of f' values

for each case. However, another form of the equation provides a more rigorous treatment of the problem necessary after the transition to the saline waters case. The energy balance of Equation (9) can be more precisely written:

$$Q_a - r(\theta_w - \theta_a) = Lk(p_w - p_a) + h(\theta_w - \theta_a) \dots\dots\dots (11)$$

where Q_a = net gain of radiant energy by a hypothetical water surface at air temperature

r = an emission coefficient for black body radiation (the change of rate of emission per unit temperature change)

and this can be rearranged as:

$$2p_w - \theta_w (1 + r/h) = Q_a/h + 2p_a + \theta_a (1 + r/h) \dots\dots (12)$$

The refinements are justified because $(\theta_w - \theta_a)$ is now liable to reach appreciable magnitude.

Equation (12) can be solved graphically in this way:

The values of Q_a , θ_a , p_a , h and the emission coefficient, r , are substituted, leaving p_w and θ_w as the unknowns. The expression can be plotted as a straight line on the vapour pressure vs. temperature chart on which is already drawn the curve of p_w vs. θ_w for the brine in question. The point of intersection of the two lines is the solution p_w , θ_w of the evaporation problem. In practice one may use a chart with a family of vapour pressure vs. temperature curves (see Fig. 2) permanently drawn on it; the straight line, Equation (12), may be lightly ruled across it to intersect points obtained by arbitrarily selecting values of either p_w or θ_w and solving for the other. Having found the unique value of p_w , evaporation itself may be computed from Equation (2) or its more convenient equivalent:

$$E = \frac{2h}{L} (p_w - p_a) \dots\dots\dots (13)$$

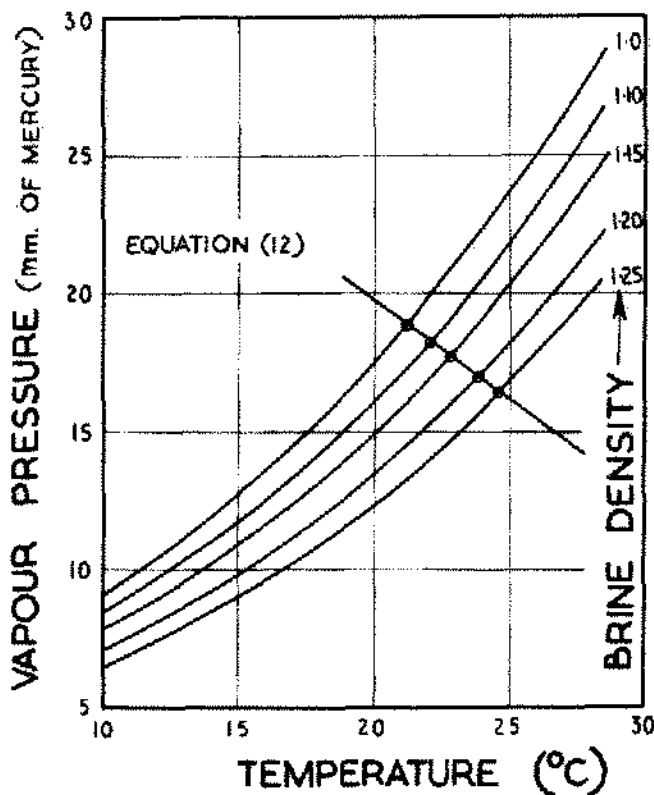


Figure 2. Graphical solution of the Ferguson equation.

The Meteorological Parameters and the Units of Expression

Q_a , Net Gain of Radiant Energy: It is possible to measure the combination of incoming and outgoing radiant energy directly, using a net radiometer, but actually it has several component streams some of which may be measured separately. It can be expressed:

$$Q_a = I_o - I_R + R_a - R_w - R_R \dots\dots\dots (14)$$

where I_o = incoming short-wave solar radiation (insolation)

I_R = insolation reflected at the water surface

R_a = incoming long-wave radiation

R_w = outgoing long-wave radiation

R_R = incoming long-wave radiation reflected at the water surface.

I_o is measured at many meteorological stations; I_R varies with the time of day, latitude, cloudiness and water surface disturbance, but for general purposes, and for periods of several days, it may be taken as roughly 4% of I_o ; R_a , R_w and R_R may be measured directly or estimated by methods like that of Penman (Penman, 1948) or Anderson (Anderson, 1952) from θ_a , p_a and cloudiness. Q_a is expressed as cal./cm.²/hr. Q_a may also be measured by means of the Cummings Radiation Integrator -- an evaporation pan interpreted in reverse (Koberg, 1958).

θ_a , Air Temperature: This is dry bulb temperature, as measured in the regular meteorological screens, and it is expressed in °C.

p_a , Water Vapour Partial Pressure of the Air: This is as measured in the regular meteorological screens by, say, wet-and-dry bulb thermometers, and it is expressed in mm. of mercury.

h, Heat Transfer Coefficient: This is a function of wind, which is the primary meteorological parameter, and it serves to represent either of the transfer coefficients, being derivable from k through Equation (8). It is empirically related to mean wind speed the height of measurement, z , of which must be specified. It also varies according to the downwind dimension (D) of the evaporating surface involved, and it may be found from c in Fig. 1, and from mean wind speed at, or extrapolated to, standard meteorological height for wind measurement (10 m.) and expressed in m./sec. Its units are cal./cm.²/hr./°C.

k , Mass Transfer Coefficient: This is related to h through Equation (8), and may in the same way be found from c in Fig. 1. It is expressed in g./cm.²/hr./mm. of mercury.

r , Emission Coefficient for Black Body Radiation: This, the rate of change of emission per unit temperature change, is expressed in cal./cm.²/hr./°C. Ferguson (Ferguson, 1952) has shown that $r = 14,400 \sigma T_a^3$ approximately. At ordinary temperatures its value remains close to 0.5.

Further Derivations of the Equation Relating to Brine

It has been shown how -- mainly on theoretical grounds but with some secondary empirical derivations -- evaporation can be computed for water and brines under a range of meteorological conditions and for ponds of varying size. To test the theory in practice the author (Bonython, 1956) made measurements with concentrated sea water in thermally-insulated ten-foot diameter pans with the particular purpose of investigating the fall off in evaporation rate with increasing salinity. The theoretical and measured curves for the change in evaporation rate with salinity (denoted by means of density of solution) are reproduced in Fig. 3. It is seen that the agreement between them, good at low salinities, is less satisfactory at the high concentrations, especially after salt has begun to crystallize.

In Fig. 4 the change of evaporation rate with salinity is shown against the more fundamental basis of the vapour pressure of the saline solutions relative to water. The 1956 data were extended by the author in February 1965, to higher salinities by measuring the evaporation of concentrated solutions of calcium chloride. To ensure uniformity of meteorological conditions for all tests a group of four specially-made U.S. Class A Land Pans insulated with polyurethane solid foam, and provided with thermographic measurement of brine temperatures, were exposed

simultaneously side by side for ten days. The pans were blackened and the brine dyed. The evaporation vs. salinity curve is also plotted in Fig. 4. It does not follow precisely the earlier one for concentrated sea water, but it is not greatly different and it extends to lower vapour pressures.

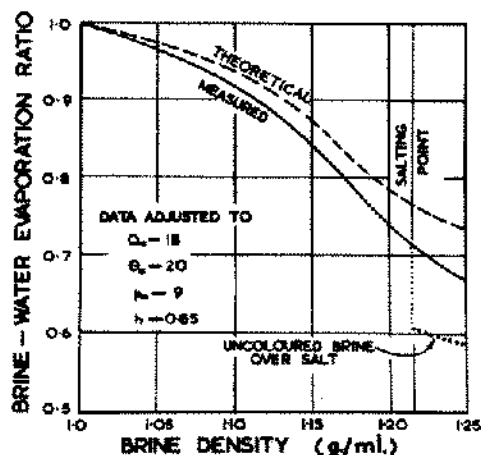


Figure 3. Effect of salinity on the evaporation rate of concentrated sea water.

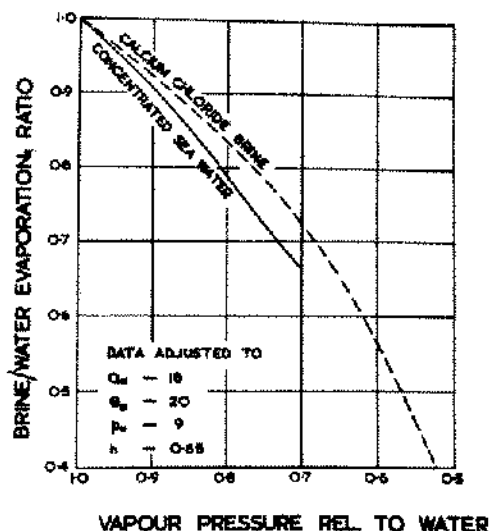


Figure 4. Evaporation lowering due to salinity plotted against vapour pressure.

The brine/water evaporation ratio vs. salinity relationship is not constant, but varies with the values of the climatic parameters, as shown by the author (Bonython, 1956). Harbeck (1955) explained the same effect in different terms. The concept of evaporation ratio has been much used in solar salting, but while it is a useful generalization its limitations should be recognized by quoting, whenever it is used, the relevant climatic parameters. The data in Figs. 3 and 4 have been adjusted by calculation to the "mean summer conditions" for Dry Creek, South Australia (Bonython, 1956, p. 69), viz.

$$Q_a = 18 \text{ cal./cm.}^2/\text{hr.}$$

$$\theta_a = 20^\circ\text{C.}$$

$$p_a = 9 \text{ mm. of mercury}$$

$$h = 0.85 \text{ cal./cm.}^2/\text{hr./}^\circ\text{C.}$$

An interesting feature of the evaporation of brines is the concurrent rise in equilibrium temperature with increasing salinity. The expression:

$$\theta_b - \theta_w = \frac{L}{h + r} (E_w - E_b) \dots\dots\dots (15)$$

where θ_b , θ_w = brine and water temperatures respectively

E_w , E_b = evaporation rate from water and brine respectively

is a consequence of Equation (11), and it shows that the relation between temperature difference and evaporation difference is independent of Q_a , θ_a , and p_a . Figure 5 shows the plot of such relations taken from the concentrated sea water and calcium chloride data, and also from some data on highly-concentrated solutions saturated with carnallite and exhibiting even larger water-brine temperature differences.

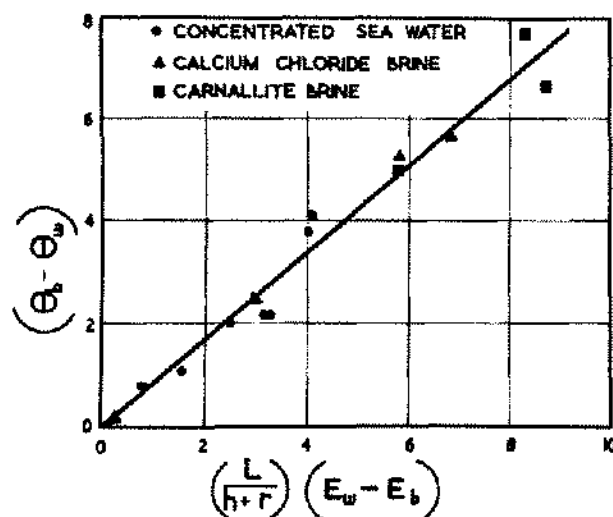


Figure 5. The evaporation difference -- temperature difference relationship of Equation 15.

APPLICATION TO FIELD CONDITIONS

Effect on Location and Design

The insight into the solar evaporation process that the foregoing treatment has given should help in the choice of the optimum climatic location for a saltfield, and of the best pond layout and operating methods. The first and most important factor to consider is rainfall -- the antithesis of evaporation. It is essential to have a locality with low annual rainfall, or at least one with low rainfall in the season having adequate evaporation.

For the evaporation itself high sunshine rate and air temperature are the most important factors, and while they usually tend to be correlated with each other, the choice of a site to which relatively hotter inland or desert air is being advected will be advantageous.

Humidity is next in importance; if the hot air referred to is also dry, as is probable, this will be beneficial, but the benefit conferred by the heat will be more important than that conferred by the dryness. Wind -- often the least significant factor -- can assume considerable importance in combination with hot, dry air.

Once the location -- and hence the climate -- is fixed there is little scope for altering the meteorological parameters, but a minor advantage can be taken in the conditions observed to prevail by, for instance, aligning the ponds normal to the prevailing wind, rather than parallel with it. There would also be another minor advantage here in placing the ponds containing the highly concentrated brines on the windward side. Nothing can be done to alter the principal factors, Q_a , Q_s , but an important field for improvement is where a practical loss of some of the potential Q_a is occurring.

Radiation Losses in the Crystallizing Ponds

So far it has been assumed that all the solar radiation penetrating the pond surface is available for the evaporation process. This is probably true in the ponds containing unsaturated brines because the floors usually consist of mud of low albedo which will absorb residual radiation and transfer it to the brine above. (Little heat is permanently exchanged through the earth beneath an evaporating pond, although there may be an appreciable, reversible seasonal effect.) Even in those ponds in the later stages of brine concentration, where there is a deposit of crystalline gypsum upon the floor, the loss of radiation by upward reflection is very low. However, when it comes to the salt crystallizing ponds the floors of which are covered with a highly-reflective crust of crystalline sodium chloride the losses of radiation may be considerable. (Bloch, Farkas, and Spiegler, 1951.) A six-inch layer of saturated natural brine over such a bed can allow as much

as 20% of the insolation to escape back into space, and this means a similar loss of evaporation. In practice the achieved evaporation rate in salt-crystallizing ponds may be well below the theoretical (see Fig. 3).

Frequently the brine of the crystallizing ponds is coloured a natural red by certain microscopic flagellate organisms, and also by bacteria, capable of thriving in it. These will help to absorb some of the radiation and so reduce the losses, but as they are in the form of a suspension rather than a true solution they cause a secondary loss by back-scattering. Some saltfield operators have considered encouraging the growth of the organisms by feeding them with nutrients, and so reducing the evaporation losses. Some actually add an organic dye to the brine with the object of entrapping all the incoming radiation.

The dye most commonly used is of the 2-Naphthol Green type. Green is not the ideal spectral colour for optimum radiation absorption, but this particular dye has adequate absorptive power, and has a combination of properties leading to its choice for the duty (Bloch and Schnerb, 1945), (Kane and Kulkarni, 1950). It is commercially available at a competitive price, it remains dispersed in true solution in natural brine and it is reasonably resistant to fading in sunlight. Concerning the last, while it does slowly fade under constant exposure to the sun and atmosphere as do all organic dyes, it has better fading resistance than other dyes tried.

Direct ways of measuring the effectiveness of dye in reducing radiation losses are by measuring absorption in the cell of an absorptiometer, or by immersing a radiometer upright in brine exposed to the sun and determining the absorption at different depths. However, these tend to give a spurious result owing to light scattering caused by the particulate organisms in the brine, and they give quite false results in a brine that contains the organisms but little or no dye. Another way is to use a downward-facing radiometer above the pond and measure the reflected radiation. In this case an allowance has to be made for radiation reflected from the pond surface itself -- radiation normally lost in any case to the evaporating process. The author developed a method using a horizontal, immersed disc 36 inches in diameter, and painted white. With the white surface -- shown to have a similar reflectance to the salt layer -- facing upwards the radiometer measures total radiation reflected by the brine surface and by the disc. By immersing the white disc at the appropriate depth below the brine surface -- usually six inches, which is a customary brine depth in crystallizing ponds -- it was possible to determine the minimum dye dosage needed to achieve approximate full entrapping of the radiation entering the pond. A concentration of 5 ppm. of "Solivap Green 150" in a six-inch layer of brine over salt crust was found to be the optimum dosage. Figure 6 shows measurements with a dyed and an undyed brine, using the radiometer and white disc.

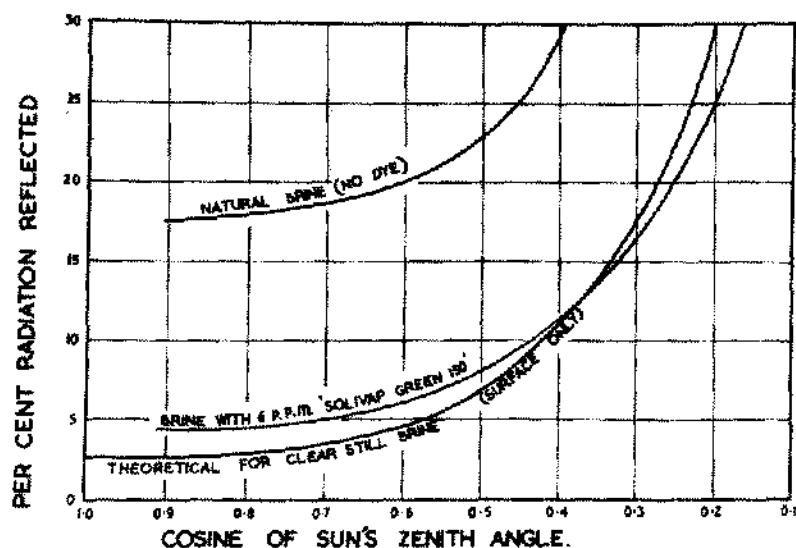


Figure 6. Radiation lost by reflection in a shallow crystallizing pond.

The effectiveness of dosing with dye can be found by direct overall measurements. At Dry Creek, South Australia, in the 1948-49 summer, a group of 58 acres of salt-crystallizing ponds treated with dye (at 1.4 times the optimum dosage that was determined only subsequently) was compared with 87 acres of an untreated control group. (See Fig. 7.) Both groups were supplied during the season with saturated brine. The result was arrived at by a materials balance for water, by measurement of the relative salt crust thicknesses and by weighing the tonnages of salt recovered per acre. The dyed ponds showed an increase in performance, salt thickness and yield of 15-20% over the undyed ones.

Dye is best introduced into the brine as it is being pumped to the crystallizing ponds. When the ponds are operated in series flow the effect is a neat one; the loss of colour by slow fading in sunlight is almost exactly counterbalanced by the tendency of the decrease of brine volume under evaporation to increase the colour concentration, with the result that the consequent degree of colour in the brine remains practically steady through the series of ponds.

Application to Pond Control

Knowledge of evaporation rate can be used in the design and operation of a solar saltfield. The simplest arrangement for the control of pumping or flow operations is to use a small, meteorological-pattern evaporation pan (preferably employing fresh water), its readings being equated to the evaporation of the various ponds by means of a pan "coefficient" and a salinity factor. Although involving an oversimplification -- pan coefficients and salinity evaporation ratios may vary seasonally -- this method has been found quite satisfactory in practice.

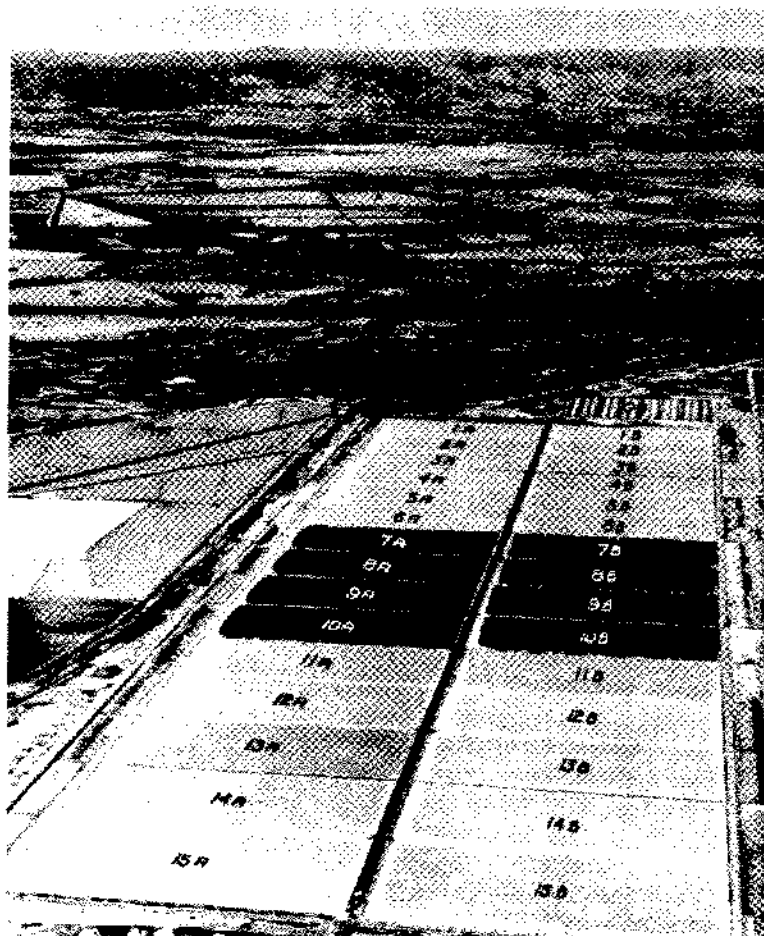


Figure 7. Dry Creek, South Australia, in 1949: aerial view of ponds treated with dye (dark) flanked by untreated ponds (light-coloured).

At the other end of the scale use may be made of evaporation calculated from first principles using the sort of equations described in this paper. It requires the accurate measurement of the four meteorological parameters which, in turn, calls for the appropriate instrumentation and skilled assistance. Because of these, and also the time factor, this method is less suited for short-term control but it is valuable for research and for historical confirmation of performance.

The first method is improved by installing a simple pan adjacent to the solar pond, taking measurements of pan evaporation, pan temperature, air temperature and wind -- or earth temperature in the case of a sunken pan -- and so making possible the correction of the pan coefficient for heat flow through the pan walls (see Kohler, Nordenson and Fox, 1958).

A simplification of the method of calculating from basic parameters is the taking of measurements of evaporation, temperatures and wind, and using a thermally-insulated pan (used as a "radiation integrator" -- Koberg, 1958), to determine indirectly the net radiant energy parameter. This is used, together with the other more readily determined parameters, in the fundamental equation to calculate evaporation rate.

SYMBOLS AND UNITS OF EXPRESSION

| Symbol | Description | Unit of Expression (Where specified) |
|------------|--------------------------------------------------------------------|---------------------------------------------------|
| c | factor relating $f(u)$ with u and D | |
| e_a | saturation water vapour pressure in the air at air temperature | |
| e_d | do. at the Dew Point | |
| f' | a function of the vapour pressure and temperature of water | |
| $f(u)$ | a function of horizontal wind speed (or mass transfer coefficient) | |
| h | heat transfer coefficient | cal./cm. ² /hr./°C. |
| k | mass transfer coefficient | g./cm. ² /hr./mm. of mercury |
| p_a | partial pressure of water vapour in air | mm. of mercury |
| p_w | vapour pressure of water surface | mm. of mercury |
| r | emission coefficient for black body radiation | cal./cm. ² /hr./°C. |
| u | horizontal wind speed | m./sec. |
| z | height above surface at which wind speed is measured | ft. or m. |
| B | back long-wave radiation to sky | |
| C | combined correction factor in energy balance | |
| D | downwind dimension of solar pond | ft. or m. |
| E | evaporation rate | |
| E_a | do. assuming $\theta_w = \theta_a$ | |
| E_b | do. specifically for brine | cm./hr. |
| E_w | do. specifically for water | cm./hr. |
| H | net gain of radiant energy | |
| I | incoming radiation (both types) | |
| I_o | incoming radiation (short-wave) | |
| I_R | short-wave radiation reflected at water surface | |
| K | heat interchange between air and water | |
| L | latent heat of vaporization | cal./g. |
| Q | net incoming radiant energy | cal./cm. ² /hr. |
| Q_a | do. assuming $\theta_w = \theta_a$ | cal./cm. ² /hr. |
| R_a | incoming long-wave radiation | |
| R_R | do. reflected at water surface | |
| R_w | outgoing long-wave radiation | |
| S | change of heat storage | |
| T_a | air temperature | °K. |
| β | Bowen Ratio | |
| γ | constant of the wet-and-dry bulb hygrometer equation | |
| λ | slope of vapour pressure -- temperature curve at air temperature | |
| σ | Stefan's constant | 5.7×10^{-12} watts/cm. ² /°K. |
| θ_a | air temperature | °C. |
| θ_b | brine temperature | °C. |
| θ_w | water temperature | °C. |

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