Design and Layout of Solar Salt Works

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ABSTRACT

The success of an ideal salt works depends mainly on the optimum design and layout. Maximum yield and higher purity of salt can be achieved by proper layout. Based on the gross yearly and seasonal evaporation rate, percolation losses, initial density of brine or seawater, number of available days, evaporation rate of different density brines and expected production, empirical relationships between these parameters are worked out. Evaporation rate of different density brines is correlated with fresh-water evaporation rate in a standard evaporimeter to obtain the appropriate surface area required for each pond holding a specific density range. Percolation losses are computed by taking 15 cm depth of saturated brine as the basis for calculations. Viscosity, density and the depth of brine are taken into consideration to obtain net losses of brine due to percolation in an earth-lined pond. The effect of initial density of incoming seawater on the ratio of crystallizer area to the remaining area is also shown in the calculations.

These computations form a guideline whenever a new salt works is to be laid out or improvement is sought in an existing salt works.

INTRODUCTION

The present process of salt manufacture by solar evaporation is based on the experience gathered through centuries and on the background of scientific knowledge of the chemistry involved in the separation of different constituents of seawater or subsoil brines. With the characteristic constancy of composition of the raw materials, the process of salt manufacture involves the same general principles. However, the total area requirement, the ratio of the area of other evaporating ponds to that of crystallizers and operational controls vary with climatological conditions and soil nature.

Meterological factors such as maximum/minimum temperatures, relative humidity, wind velocity, incident solar radiation, rainfall and total number of clear days have been considered so far to estimate the exact evaporation rate of brine. Most of the time these extremely elaborate formulae fail to give ultimate correct values in spite of taking every factor into consideration. What is needed is the exact gross evaporation rate of fresh water from a standard evaporimeter which can be used for computing brine evaporation rate.

Percolation of brine through a soil bed at all evaporating stages is an elusive but important factor that has been neglected so far because of its complexity. Though it is impracticable to measure permeability of the entire area under consideration, percolation values computed from the particle size analysis of representative soil samples will definitely lead to a fairly accurate approximation of brine lost through the soil.

This paper summarizes the importance of these two factors in designing a solar salt works with the help of empirical formulae for calculating area of any pond for a given evaporation rate, percolation and nominal design production level.

RATE OF BRINE EVAPORATION

Fresh Water Evaporation

Fairly accurate values of the rate of brine evaporation can be calculated if gross fresh water evaporation rate is known from a standard evaporimeter. The calculations in subsequent paragraphs are based on the values obtained from a standard U.S. 'A' pan evaporimeter of 1220 mm dia and 250 mm water depth. The evaporimeter is kept on a wooden frame of 100 mm thickness. The recorded gross evaporation rate is found to be 23% to 35% higher than the actual rate of evaporation from large bodies of water (Houk, 1960). To obtain the net evaporation rate, the observed gross values, E(mm/day) are multiplied by an average factor of 0.7 (F_1).

The brine evaporation rate is lower than that of fresh water. It is proportional to the lower vapour pressure of brine (Bonython, 1966). Another factor, F_2, is used to obtain brine evaporation rate from fresh water evaporation rate. The values of F_2 are shown in Table 1 for 0 to 30°Be′ density brines of marine-origin (Bawdekar, 1964).

Basis: $F_2 = 1 - 0.012\,x$ (for 0-25°Be′)
$F_2 = 1.450 - 0.03\,x$ (for 25-30°Be′)

where x = density of brine in °Be′

$$\text{Brine evaporation rate} = E \times F_1 \times F_2 \text{ mm} \quad (1)$$

where

E = gross evaporation rate of fresh water, mm
F_1 = Conversion factor (value ranging from 0.65-0.77 but taken as 0.7).
F_2 = Conversion factor from Table 1 for the required density of brine.

Volume-density Relationship

In a system where no solids separate out, the product of $(d - 1)$ and y is constant where d is the density of brine in g/cm^3 and y is the volume. During the crystallization stage, the volume first changes rapidly and then more gradually as the vapour pressure rises. Based on these two facts the density-volume relationship has been computed and is presented in Table 2.

Data from Table 1 and 2 are used in calculating the area of individual compartment and volume requirement of desired density brine.

PERCOLATION

Brine leakage from solar evaporation ponds constitutes one of the major factors in the design, operation and economics of salt recovery. Study of the nature of the soil used in lining the ponds is therefore an essential step before designing a salt works. The majority of the soils near the seacoast are alluvial in nature showing strong stratification. This property makes exact measurement of percolation very difficult. But a designer, with some broad guidelines, should be able to design a fairly reasonable plan.

TABLE 1

Density-Evaporation Relationship (Valeus of F_2)

Density °Be′	Evaporation	Density °Be′	Evaporation	Density °Be′	Evaporation
0	1.000	10	0.880	21	0.748
1	0.988	11	0.868	22	0.736
2	0.976	12	0.856	23	0.724
3	0.964	13	0.844	24	0.712
3.5	0.958	14	0.832	25	0.700
4	0.952	15	0.820	26	0.670
5	0.940	16	0.808	27	0.640
6	0.928	17	0.796	28	0.610
7	0.916	18	0.784	29	0.580
8	0.904	19	0.772	30	0.550
9	0.892	20	0.760		

TABLE 2

Density-Volume Relationship

Density °Be′	Volume	Density °Be′	Volume
1	3.5618	16	0.1995
2	1.7686	17	0.1863
3	1.1708	18	0.1746
3.5	1.0000	19	0.1641
4	0.8719	20	0.1546
5	0.6926	21	0.1461
6	0.5731	22	0.1383
7	0.4877	23	0.1312
8	0.4236	24	0.1246
9	0.3738	25	0.1188
10	0.3340	26	0.0721
11	0.3013	27	0.0521
12	0.2742	28	0.0403
13	0.2512	29	0.0330
14	0.2315	29.5	0.0280
15	0.2144		

Soil Classification

Classification of soils based on the International Soda Pipette Method (Piper, 1950) is the most suitable guideline to predict the extent of leakage of brine. It is based on particle size classification into four types, depending on particle diameter. The mineral matter of the soil is separated from organic matter, gypsum, calcium carbonate and soluble salts. It is then classified into four groups of coarse sand by wet sieving and then into fine sand, silt and clay by the sedimentation method.

Coarse sand	0.2—2.0 mm
Fine sand	0.02—0.2 mm
Silt	0.002—0.02 mm
Clay	Below 0.002 mm

A gradation curve is obtained by plotting particle diameter on a logarithmic scale and cumulative percentage on an arithmetic scale. Porosity factor, n, at field density is estimated by standard procedure. Average particle diameter, D_{50}, is read from the gradation curve. Uniformity coefficient, C_u, which is the ratio of D_{60} to D_{10} is also obtained from the gradation curve. Based on Kozeny's equation (Kozeny, 1927) and its further modification (Joshi, 1970) the permeability coefficient is calculated with the help of the following equation:

$$k = \frac{n^3(D_{50})^2}{(1-n)^2(C_u)^{1.766}} \times 6.25 \times 10^3 \quad (2)$$

where

k = permeability coefficient, mm/day
n = porosity factor

D_{50} = Average particle diameter at 50% on the gradation curve, mm
C_u = Uniformity coefficient, D_{60}/D_{10}.

Based on the particle size distribution in the three groups (sand, silt and clay) soils have been classified into three major classes and ten different types as shown in Table 3.

Percolation Rate

Using Equation 2, the average rate of percolation of brine of 25°Be′ (density of brine at the salting point) is calculated and shown in the last column of Table 3. The first three soils have very high percolation rate. They are unsuitable for salt works. Next three (No. 4, 5 and 6) are moderately suitable, whereas the last four are most suitable as far as loss due to percolation is concerned. The values of percolation are calculated from the average of each type of particles with ideal particle size distribution and smooth gradation curve. Highest values of the uniformity coefficient are assumed. It would be necessary, therefore, to compute the percolation losses from actual analysis of the soil using Equation 2.

As the brine proceeds progressively from reservoir to crystallizer its depth decreases (unless new brine is added) and density and viscosity increase. Because these three properties have pronounced effect on the quantity of brine lost through the soil bed, appropriate corrections are made to arrive at absolute values of percolation.

AREA REQUIREMENT

The area of a solar salt works is subdivided into different compartments to facilitate the flow of brine and to control the density. The different evaporating ponds, their density range and average depth of brine are shown in Table 4.

TABLE 3

Classification of Soils and Their Percolation Rate

Class		Type	Percentages			Percolation of saturated brine, mm/day
			Sand	Silt	Clay	
Sandy	(1)	Sand	92–100	0–8	0–8	480.00
	(2)	Sandy loam	70–92	0–12	0–12	97.44
	(3)	Loamy sand	62–65	5–25	8–35	5.78
	(4)	Sandy clay	50–75	0–7	25–50	0.45
Loamy	(5)	Loam	50–75	10–25	10–25	0.36
	(6)	Silty loam	0–75	25–100	0–25	0.24
	(7)	Silty clay loam	0–50	25–75	25–40	0.20
	(8)	Clay loam	35–70	8–25	25–40	0.15
Clayey	(9)	Silty clay	0–35	25–60	40–75	0.12
	(10)	Clay	0–64	0–25	30–100	0.10

The area of crystallizers forms the basis for computing the area of other evaporating ponds. The crystallizer area is directly proportional to the nominal production level and inversely proportional to the rate of evaporation and number of crystallization days. Once the crystallizer area is known, the relative area of other ponds can be computed.

Area Calculations

To derive an empirical formula to calculate the crystallizer area, the following factual data of the Bhavnagar Salt Works is considered. A model salt works with a production capacity of 5000 tonnes per annum is assumed.

Average daily evaporation (Oct–May) = 7.4712 mm
Number of crystallization days = 150
Targeted production per year = 5000 tonnes
Daily average production = 33.333 tonnes.

Saturated Brine Requirement

Tray experiments indicate that one litre of saturated brine (25°Be′) yields 222 g of sodium chloride on reaching 29.5°Be′ or 1 t of salt production will require 4.5 m^3 of saturated brine. Assuming 90% efficiency of salt harvesting, the saturated brine required to produce 33.333 *t*/day works out to be 166.67 m^3.

Crystallizer Area

Volume of 25°Be′ brine = 166.67 m^3

$$\text{Volume left at } 29.5°\text{Be}' = \frac{166.67 \times 0.028}{0.1188} \quad \text{(Ref. Table 2)}$$
$$= 39.28 \text{ m}^3$$

Volume of water to be evaporated = 166.67 − 39.28
= 127.39 m^3

Average evaporation rate of 27.25°Be′ = 7.4712 × 0.7 × 0.6325
(Equation 1)
(Value of F_2 from Table 1)
= 3.308 mm/day

Area = 127.39 ÷ 0.003308
= 38510 m^2.

Area of Other Ponds

Using the method described above, the area of evaporating pond compartments *B* to *J* is calculated and presented in Table 5.

Empirical Formula for Crystallizer Area

Using the data and assumptions made in the preceding paragraphs, an empirical formula is worked out to compute crystallizer area. All the factors are listed below:

1. Nominal annual production = T tonnes
2. Volume of saturated brine required per tonne = Q m^3
3. Volume of bittern left at 29.5°Be′ per tonne = S m^3
4. Number of crystallization days per annum = D
5. Gross evaporation rate of fresh water/day = E mm
6. Conversion factor for fresh water evaporation (equation 1) = F_1
7. Conversion factor for brine evaporation = F_2
8. Efficiency factor of salt harvesting = 0.9.

$$\text{Area for crystallizer} = \frac{T}{D}\frac{(Q-S)}{0.9} \times \frac{1000}{E \times F_1 \times F_2} m^2$$

Substituting values of the known factors, i.e.,

$Q = 4.5\ m^3$, $S = 1.0606\ m^3$, $F_1 = 0.7$

and $F_2 = 0.6325$

$$A = \frac{T}{D}\frac{(4.5 - 1.0606)}{0.9} \times \frac{1000}{E \times 0.7 \times 0.6325} \text{ m}^2$$

Area of Other Pond Compartments

Once the area of crystallizer is known, the area of the other pond compartments (B to J) is obtained by multiplying A with the values of R shown in the last column of Table 5.

$$\text{Area of any compartment } (B \text{ to } J) = \frac{0.8631\ TR}{DE}\ ha \quad (4)$$

AREA REQUIREMENT WITH PERCOLATION

Because brine is lost continuously due to percolation, makeup brine and additional area for it must be provided to achieve the targeted production. To compute the area of different compartments the following four assumptions are made based on practical experience in the field:

1. Percolation through the crystallizer beds is assumed to be zero, as the initial salt layer makes the bed almost impervious. However, in the beginning of every crop, some percolation is experienced which may amount to a fraction of a millimeter for a few days. If the salt works is laid on pervious soils, the crystallizer area is given clay treatment, as one cannot afford to lose the saturated brine.
2. In the compartments B and C, density-viscosity correction not applied because the brine of the penultimate compartment (B) is very near to saturation. Compartment C is lined by the deposition of gypsum (17-23°Be′), which checks percolation to some extent.
3. In condensers D to E, an increase in depth and decrease in viscosity enhance the percolation 1.67 times compared to saturated brine of 25°Be′ with 150 mm depth. Similarly, in compartments F to J, the ponds containing the least concentrated waters, the enhancement is 2.088 times. These two corrections have been considered in calculating the necessary pond area.
4. Percolation rates of 0.5 to 3.0 mm/day with an increment of 0.5 mm are considered for calculations with 150 mm depth of saturated brine.

TABLE 4

Details of Ponds

Compartment	Code	Density Range °Be′	Average Density °Be′	Depth mm
Crystallizer	A	25-29.5	27.25	150
Condenser I	B	23-25	24.0	150
Condenser II	C	17-23	20.0	200
Condenser III	D	14-17	15.5	250
Condenser IV	E	10-14	12.0	275
Condenser V	F	6-10	8.0	300
Reservoir I	G	3.5-6	4.75	400
Reservoir II	H	3.0-3.5	3.25	400
Reservoir III	I	2.5-3.0	2.75	400
Reservoir IV	J	2.0-2.5	2.25	400

TABLE 5

Area of Crystallizers and Other Evaporating Ponds

Compartment	Code	Density range °Be′	Area m^2	Ratio of compartment area to crystallizer area R
Crystallizer	A	25-29.5	38,510	1.0000
Condenser I	B	23-25	4,665	0.1211
Condenser II	C	17-23	19,445	0.5049
Condenser III	D	14-17	14,892	0.3867
Condenser IV	E	10-14	32,112	0.8338
Condenser V	F	6-10	70,930	1.8418
Reservoir I	G	3.5-6	1,21,395	3.1522
Reservoir II	H	3.0-3.5	47,664	1.2377
Reservoir III	I	2.5-3.0	66,303	1.7217
Reservoir IV	J	2.0-2.5	98,858	2.5670

Area of Condenser B (*23-25°Be′*)

To feed the required quantity of saturated brine to the crystallizers, an additional quantity of 23°Be′ brine equivalent to percolated (lost) brine has to be made up in order to maintain production. Obviously an additional concentration area also would be needed. Table 6 shows the volume of average 24°Be′ brine lost and total area required for each percolation rate. Data from Tables 1 and 2 are used in these calculations.

Area of Compartments C to J

In a similar way, the brine requirement for the remaining compartments has been calculated from the preceding compartment area and is presented in Table 7.

TABLE 6

Area for B (23–25°Be') for Different Percolation Rates

Percolation mm/day	Volume of 23°Be' m^3	Percolated volume of 24°Be' m^3	Percolated volume of 23°Be' m^3	Total volume of 23°Be' m^3	Area m^2
0.0	184.05	Nil	Nil	184.050	4665
0.5	184.05	2.332	2.453	186.503	4727
1.0	184.05	4.664	4.906	188.956	4789
1.5	184.05	6.966	7.359	191.409	4851
2.0	184.05	9.328	9.812	193.862	4914
2.5	184.05	11.660	12.265	196.315	4976
3.0	184.05	13.992	14.718	198.768	5038

TABLE 7

Area of Compartments (m^2) for Different Percolation Rates

Compartment	Density °Be'	Percolation Rate, mm/day of 25°Be' brine						
		0.0	0.5	1.0	1.5	2.0	2.5	3.0
A	25–29.5	38,510	38,510	38,510	38,510	38,510	38,510	38,510
B	23–25	4,665	4,727	4,789	4,851	4,914	4,976	5,038
C	17–23	19,445	20,575	21,704	22,836	23,966	25,099	26,229
D	14–17	14,892	16,394	17,899	19,403	20,907	22,411	23,915
E	10–14	32,112	37,590	43,171	48,553	54,035	59,513	64,995
F	6–10	70,930	91,897	1,13,651	1,33,497	1,54,712	1,75,658	1,96,609
G	3.5–6.0	1,21,395	1,72,114	2,24,265	2,73,260	3,24,282	3,75,013	4,25,732
H	3.0–3.5	47,664	69,141	91,205	1,11,986	1,33,611	1,55,094	1,76,576
I	2.5–3.0	66,303	99,235	1,33,004	1,64,968	1,98,200	2,31,033	2,63,965
J	2.0–2.5	98,858	1,52,904	2,08,195	2,60,777	3,51,149	3,69,155	4,23,211

TABLE 8

Area for Condenser + Reservoir for Different Starting Densities and Percolation Rates and Ratio of Condenser + Reservoir to Crystallizing Area

Percolation mm/day	Initial density	Area m^2 3.5°Be'	3.0°Be'	2.5°Be'	2.0°Be'
0.0	Area	2,63,439	3,11,103	3,77,406	4,76,264
	Ratio	6.84	8.08	9.80	12.37
0.5	Area	3,43,297	4,12,438	5,11,673	6,64,577
	Ratio	8.91	10.71	13.29	18.56
1.0	Area	4,25,479	5,16,684	6,49,688	8,53,883
	Ratio	11.05	13.42	16.87	22.28
1.5	Area	5,02,400	6,14,386	7,79,354	10,40,131
	Ratio	13.05	15.95	20.24	27.01
2.0	Area	5,82,816	7,16,427	9,14,527	12,65,676
	Ratio	15.13	18.60	23.75	32.87
2.5	Area	6,62,669	8,17,763	10,48,796	14,17,951
	Ratio	17.21	21.23	27.23	36.82
3.0	Area	7,42,518	9,19,094	11,83,059	16,06,270
	Ratio	19.28	23.87	30.72	41.71

Effect of Initial Density of Seawater

If the initial density of seawater is below 3.5°Be', i.e., the seawater is somewhat diluted by meteoric inflow, additional area must be provided to attain seawater concentration (3.5°Be'). The ratio of the area of the other necessary evaporating ponds to that of crystallizer will increase with lowering of the initial density. Considering this fact, such ratios have been calculated for four initial densities (3.5, 3.0, 2.5 and 2.0°Be') and for all the percolation rates (0.5, 1.0, 1.5, 2.0, 2.5 and 3.0 mm/day), as shown in Table 8.

The extent to which the percolation rate and the initial density of seawater affect the area of reservoir and condenser is shown in Figure 8. The ratio of area of reservoir + condenser to area of crystallizer increases from 6.84 for 3.5°Be' initial density without percolation to 41.71 for 2°Be' initial density with 3.0 mm/day percolation.

Production of salt per hectare of area calculated from the 5000 *t* per annum model salt farm is given in Table 9. Production values in the box indicate economical production, which is 80 *t* per hectare fo the conditions of evaporation rate, number of days and F_1 values mentioned in Table 9.

Area of Other Ponds with Percolation

To calculate the area of any condenser or reservoir for a given percolation rate, values in Tables 5 and 7 are used in the following formula:

$$A = \frac{0.8631\ T\,RR'}{DE} \qquad (5)$$

where

A = Area of the compartment in hectares
T = Nominal annual production in tonnes
R = Ratio of evaporating ponds to crystallizers area (Table 5)
R' = Ratio of area obtained from Table 7.

$$= \frac{\text{Area for } P \text{ mm percolation}}{\text{Area for zero percolation}}$$

D = Number of crystallization days per annum.
E = Gross fresh water evaporation rate, mm/day.

An example given below shows the actual calculations.

Compartment under consideration—Condenser of 10–14°Be'

Nominal annual production—1,00,000 *t*
Gross evaporation of fresh water—6 mm/day
Number of crystallization days—200
Expected percolation rate—1.5 mm/day

$$A = \frac{0.8631 \times 1{,}00{,}000 \times 0.8338}{200 \times 6} \times \frac{48533}{32112} = 90.63\ ha$$

$$\text{Value of } R' = \frac{48533}{32112} \text{ (from Table 7)}$$

In this way, area of any other necessary compartment sizes can be worked out.

SEAWATER REQUIREMENT

Daily requirement of seawater is based on three parameters, (1) Volume lost due to percolation, (2) volume lost through evaporation, and (3) volume charged in the crystallizers. The first parameter is almost constant, depending on the soil nature, but evaporation rate in winter is about 40% of the rate in summer. Therefore, in order to find out the daily requirement of seawater, the following formula is used:

$$V = Vp + Va \times \frac{Ed}{E} \qquad (6)$$

where

V = Volume of sea water required on a particular day
V_p = Volume percolated equivalent to sea water
Va = Average daily requirement
E = Gross average fresh water evaporation rate
Ed = Gross fresh water evaporation on the particular day.

CONCLUSION

In designing a solar salt works, evaporation rate of fresh water, number of clear days in a year, soil nature, initial seawater density, nominal production level and percolation rate are considered as governing factors.

TABLE 9

Production of Salt per Hectare of Total Area
(E = 7.4712 mm/day, D = 150, F_1 = 0.7)

Percolation mm/day	Production per hectare for initial density of 3.5°Be'	3.0°Be'	2.5°Be'	2.0°Be'
0.0	165.59	143.02	120.21	97.13
0.5	130.95	110.88	90.88	71.11
1.0	107.96	90.06	72.65	55.78
1.5	92.37	76.58	61.13	46.35
2.0	80.47	66.23	52.46	38.34
2.5	71.31	58.39	45.98	34.53
3.0	64.02	52.16	40.93	30.40

Based on this data the area of crystallizers, condensers and reservoirs is calculated by employing empirical formulae. Volume density relationships and brine evaporation rate with respect to fresh water evaporation rate form the basis for computing pond area requirement and daily seawater requirement for an optimal lay-out of a simple solar salt works.

REFERENCES

Bavdekar, P. R. 1964. Theory of Solar Salt Manufacture, Seminar on Salt and Byproducts, April 10–11, 1964, Bhavnagar, India.

Bonython, C. W. 1966. Factors Determining the Rate of Solar Evaporation in the Production of Salt, Second Symposium on Salt, Northern Ohio, Geol. Soc., Cleveland, Ohio.

Houk, I. E. 1960. Irrigation Engineering, John Wiley and Sons, Inc. New York, Vol. 1, 260.

Joshi, B. S. 1970. Studies on Soils, Ph.D. Thesis, Gujarat University, Ahmedabad, India.

Kozeny, J. 1927. Ber. Wein. Akad., 136-a, 271.

Piper, C. S. 1950. Soil and Plant Analysis, Adelaide, Australia.