Solar Pond Design for the Production of Potassium Salts from the Salar de Atacama Brines

Fernando Ide, Luis Vergara-Edwards and Pedro Pavlovic-Zuvic
Comité de Sales Mixtas—CORFO
Santiago, Chile

ABSTRACT

The feasibility of producing potassium salts from the Salar de Atacama brine deposits in northern Chile using solar evaporation depends essentially on the construction of large, inexpensive clay bottomed ponds. Clays of good quality and in sufficient quantity for pond construction were found under the salt crust at the northern boundary of the central nucleus of the Salar. Field and laboratory permeability tests were performed. An experimental pond was also constructed on top of the in situ clay to run leakage tests. The pond area required for the production of 520,000 tons per year of potassium chloride and 150,000 tons per year of potassium sulfate was calculated through use of material balances for each crystallization stage. The basic design of the solar pond described here was proposed by Saline Processors Inc. The estimated brine reserves of the Salar will be presented also.

INTRODUCTION

The Salar de Atacama is the largest solar salt works [salar] in northern Chile. The first extensive survey of this Salar was done in 1969 by the Instituto de Investigaciones Geológicas, which reported high lithium and potassium concentrations in the brine deposits, filling the pores of the salt mass.

CORFO, the Government Development Agency, started in 1971 the work to evaluate the ore body's potential and economic merit. For this purpose access roads to the Salar were constructed. Then, sampling and drilling programs were performed along a 25-kilometer access road to the salt nucleus.

During the period extending from 1975 to 1979, with the technical assistance of Saline Processors Inc., CORFO carried out detailed development studies. The main following subjects were covered: brine reserves evaluation, clay exploration, solar pond design and construction, evaporation rates and phase chemistry studies, process design and economic estimate for the production of potassium salts. Further on, CORFO completed an extensive survey of a large clay deposit on the north side of the Salar nucleus. At the same time, additional work on solar pond design and construction was done.

GENERAL CHARACTERISTICS OF THE SALAR DE ATACAMA

The Salar de Atacama, extending from latitude S 23° to S 23° 45′ and from longitude W 68° 05′ to W 68° 30′, was formed as the terminal evaporation basin of a large drainage system (Figure 1). The basin covers approximately 3,000 km^2 and the salt nucleus proper about 1,400 km^2. The floor of the Salar lies at an elevation of 2,300 meters. The salt nucleus consists almost exclusively of halite. The surface is generally formed by cracked and uplifted salt crusts, reaching up to 0.80 meter high. A roughly constant brine level is about 0.60 meter below the surface. There is a continuous water discharge into the Salar, entering mainly as spring or ground water, being the principal source the San Pedro river (north of the Salar).

The Salar de Atacama basin has one of the highest evaporation rates of the world. This is due to a strong solar radiation, very low relative humidities (figures as low as 5% have been recorded), winds of moderate intensity that in the afternoon may exceed 90 km/hr (Stoertz, 1974) and minimal rainfall (20 to 50 millimeters annually). Temperatures through the year may vary between -1°C to 35°C.

Because the Salar surface is not accessible to conventional vehicles, nearly 100 kilometers of roads have been constructed.

BRINE RESERVES

The brine filling the void spaces of the salt mass represent the ore value of the Salar.

Fairly extensive brine samples have been taken over the central nucleus from shallow pits dug along the access roads. Also an exploration program over about 840 km2 was executed with helicopter support and portable drilling

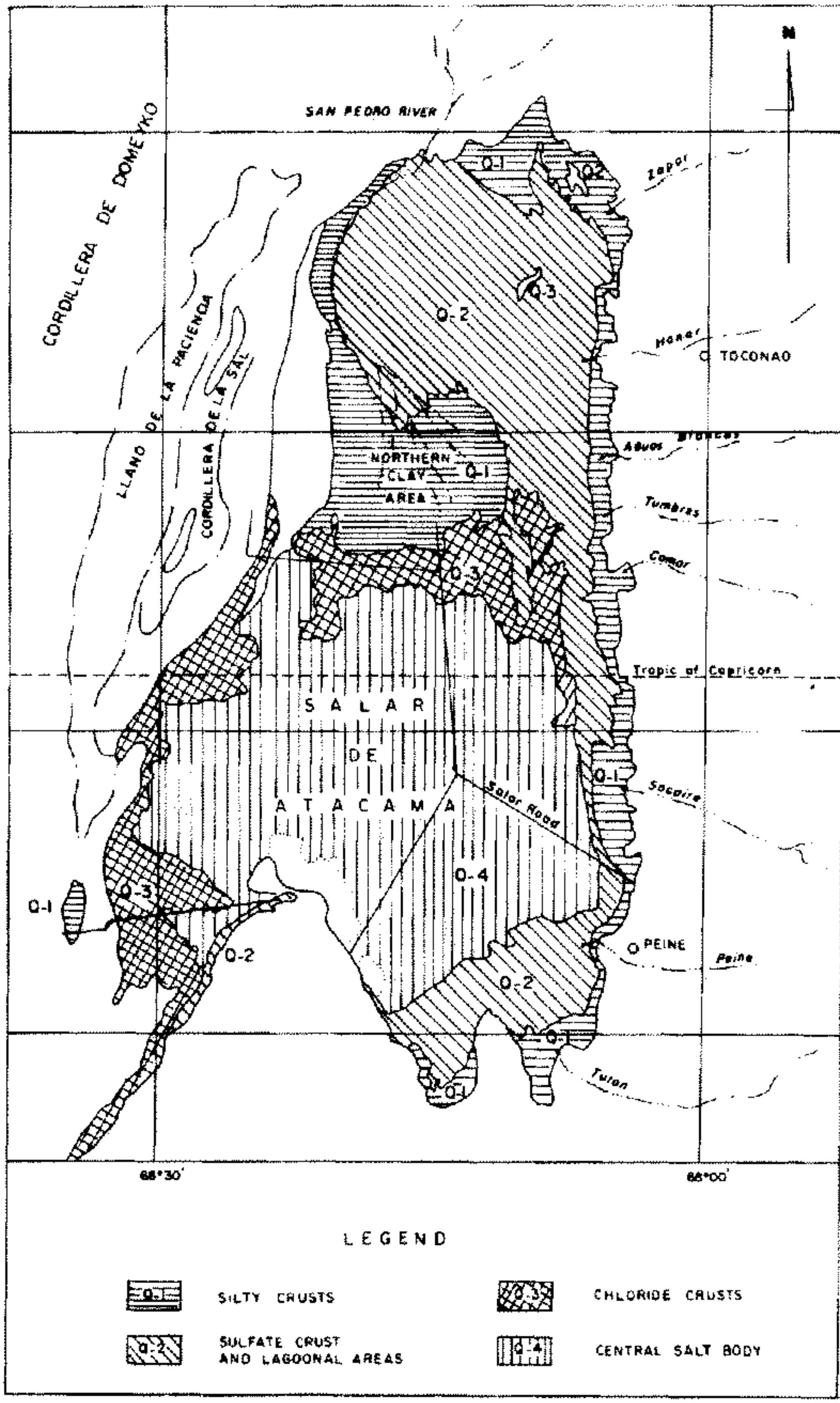

Figure 1. Geological Map of Salar de Atacama.

and pumping equipment (Kunasz, 1982). Chemical analyses made on all available samples allowed the construction of isopach maps showing the principal ions of interest. (Figure 2 illustrates the isopachous lines for potassium).

Drillings over various parts of the nucleus were performed, ranging from 40 to 390 meters depth. Porosity measurements on the cores retrieved show that the near surface portion of the halite crust has a high porosity, decreasing rapidly with depth. The average effective porosity for the upper 20 meters of salt was 10%.

A seismic survey performed along a 10-kilometer strip of the principal Salar access road (Figure 1) revealed two different zones: an upper high porosity zone (18%) to a depth of 25 meters and a low porosity zone (8%) from 25 to 40 meters (Behn, 1976).

Several wells were drilled along the same access road to run pumping tests to determine the hydraulic characteristics of the aquifer and performance of the wells (pumping rate and drawdown). Most wells were capable of pumping at least 30 1/sec with almost no drawdown. A high transmissivity was obtained only for the upper 30 meters.

A correlation between the potassium content of the brine and the specific yield was found (Ide, 1978) and is presented in Figure 2. With the specific yield data (connected porosity), determined for a depth of 30 meters, it was possible to calculate the effective volume of brine. This information, together with the concentration isopachs, was used to estimate the reserves of the principal elements of interest over a surface of approximately 1300 square kilometers of the Salar nucleus (Table 1).

SOLAR EVAPORATION

Over a period of seven years (1976–1982) a great deal of information was gathered to calculate the evaporation rates of brines at the Salar. For this purpose a series of small metal pans (1 m to 3 m diameter and 0.4 m to 0.6 m high), without insulation were installed at the Salar.

The evaporation rates were controlled by measuring the free board drop of the pans. The compiled data over the indicated period of time are presented in Table 2.

The evaporation rates shown in Table 2 are valid only for metal pans of the same size and without insulation. The evaporation rate in a pan is higher than in large ponds. To establish the pan to pond relationship a 40 m by 40 m PVC-lined test pond was constructed. A leak-tight evaporation pan was installed at the pond area. Using similar brines the liquid level drop was measured in the pond and pan for one year. A scale factor of 0.71 for the evaporation rates was determined (on an annual basis).

CLAY AVAILABILITY FOR SOLAR PONDS

The low-cost processing of the Salar de Atacama brines by using solar evaporation for brine concentration and the crystallization of salts requires the construction of large, inexpensive solar ponds. The least expensive and most serviceable ponds can be constructed by native, in-place, satisfactorily impermeable clays. From the commencement of the study program on the Salar big exploration efforts were made to locate a suitable clay area for pond construction.

Clays of excellent quality were discovered in 1977 under the salt crust, to the north of the Salar, in the delta region of the San Pedro River (Figure 1). During the winter of 1978 an exploration survey started and roads were constructed into the area. The types of sediments found in the upper two meters below the salt crust include thin beds of silt or sandy silt within the clay beds. Also gypsum as moderately thin strata up to one meter thickness occurs throughout the clay area.

A 0.5 km grid was sampled over about 100 km^2 by means of simple hand augers. This tool makes a hole roughly 5 cm in diameter and takes a sample of 20 cm in length for each sample run.

Nearly 400 holes were drilled to depths ranging from 1 meter to 4 meters, with an average of 2 meters. The clay samples were qualitatively judged in the field to get information about thickness and the continuity of good clays, a good clay being one with a permeability less than 2.5×10^{-7} cm/sec. The aggregate thicknesses of good quality clay beds reported in the samples descriptions were used to draw isopach maps (Morales, 1981). Summary maps of clay thickness and depth are seen in Figures 3 and 4.

The surface of the sediments in the area explored for clays is covered with an extensive crust of halite ranging from a simple moderately smooth silty crust of up to 20 cm, to a heavily heaved crust of up to one meter in thickness. The most common salt crust thickness is in the order of 25 cm. The clay in most areas has groundwater immediately below, under a slight pressure. This water is a sodium chloride saturated brine and contains moderate amounts of trapped air. As a result of this occurrence, the clay is normally moist and quite plastic.

Permeability tests (falling head permeameter) were run on several clay samples (cores) with results indicating permeabilities in the range of 2.5×10^{-7} cm/sec to 8×10^{-8} cm/sec. Field permeability tests were likewise performed in different locations of the clay area by driving two-meter lengths of 10″ diameter pipe into the clay and then filling the pipe with brine (Morales, 1981). A cap of oil was poured over the surface of the brine to prevent evaporation. Measurements were taken over a period of several months, which yielded permeability results on the order of 5×10^{-7} cm/sec to 3×10^{-8} cm/sec.

To corroborate the permeability figures obtained through the pipe test and to prove the continuity of the clay deposit a 100 m by 100 m pond was constructed on top of the in situ clay. This experimental pond was also useful to develop a method of pond construction.

The area was first roughly flattened with a bulldozer.

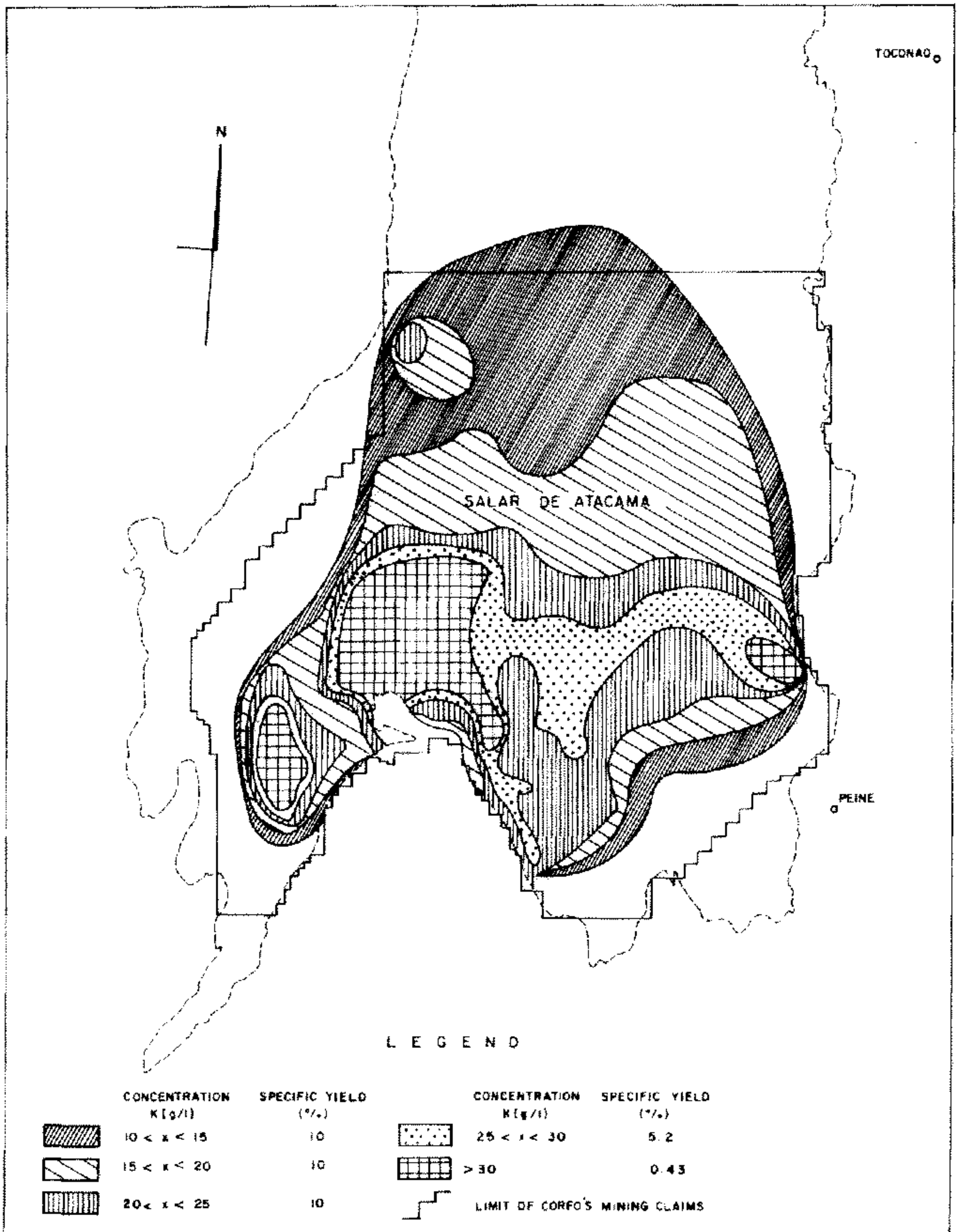

Figure 2. Isopachous lines for potassium concentration.

TABLE 1

Estimated Reserves in the Nucleus of the Salar de Atacama

Element	Reserves (Million tons)
K	58.0
Mg	30.5
Li	4.5
B	2.9

TABLE 2

Average Evaporation Rates for Water and Various Density Brine

Density (g/l)	Summer(*) (mm/day)	Winter(**) (mm/day)	Annual (mm/day)
1,000	13.0	7.0	10.5
1,226–1,260	8.0	4.0	6.3
1,260–1,290	7.3	3.7	5.8
1,290–1,310	5.7	3.0	4.6

(*) September to March
(**) April to August

Next the dikes 1 m high were built with the removed crushed salt crust. The internal sidewalls (slope of 1 to 3) were lined with a 30-cm layer of good quality clay. To avoid horizontal leakage an internal trench was excavated on the whole perimeter of the pond, 60 cm wide and 50 cm deep to the underlying clay bed. This trench was filled with good quality clay, placed in successive compacted layers.

The pond was filled with brine to a height of 50 cm. During a 5-month period (August to December 1979) the leakage of this solar pond was estimated by measuring the brine level change in the pond compared with the level

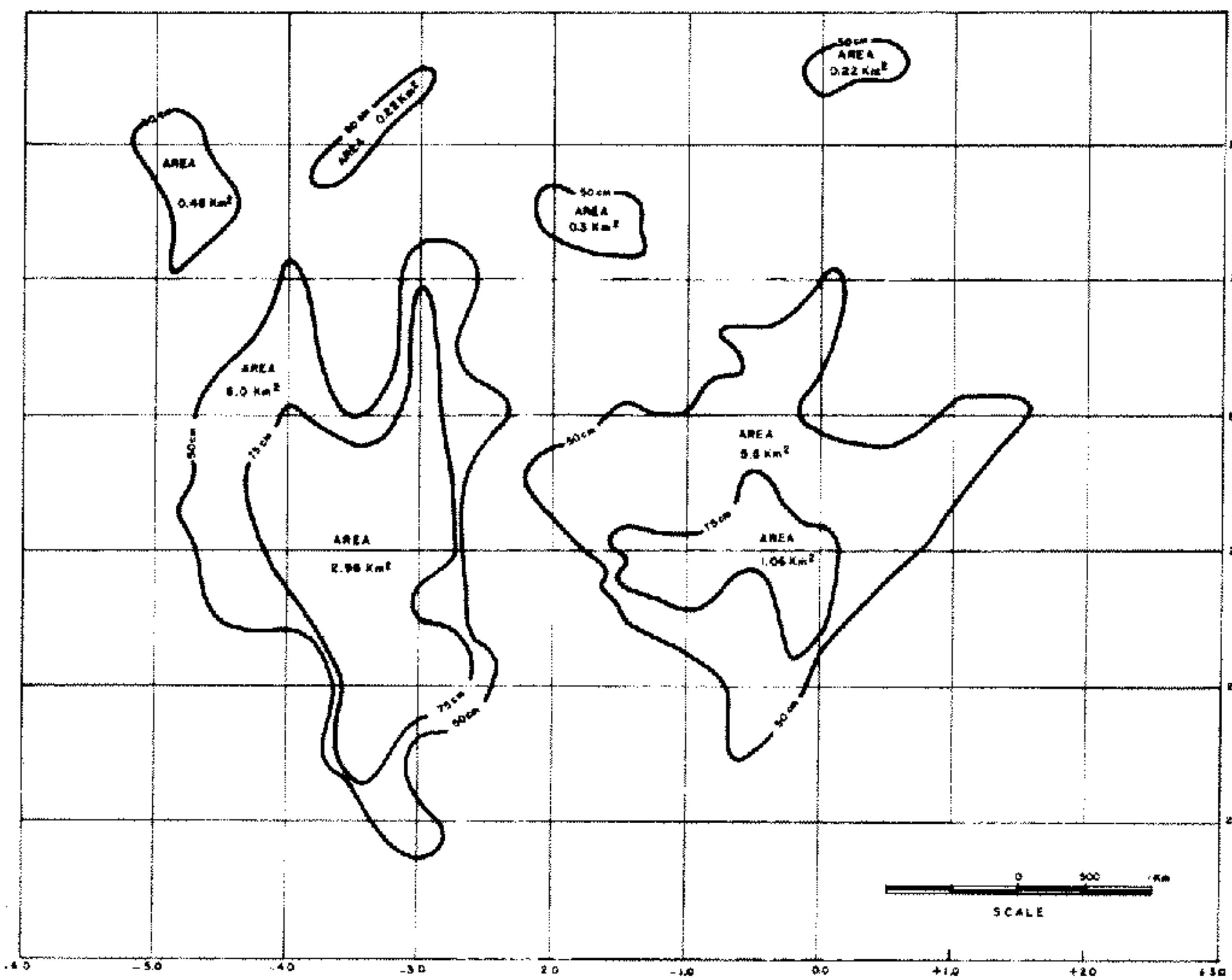

Figure 3. Clay isopachous lines to one-meter depth showing aggregate clay thickness of at least 50 cm overall (over 12 km² good quality clay).

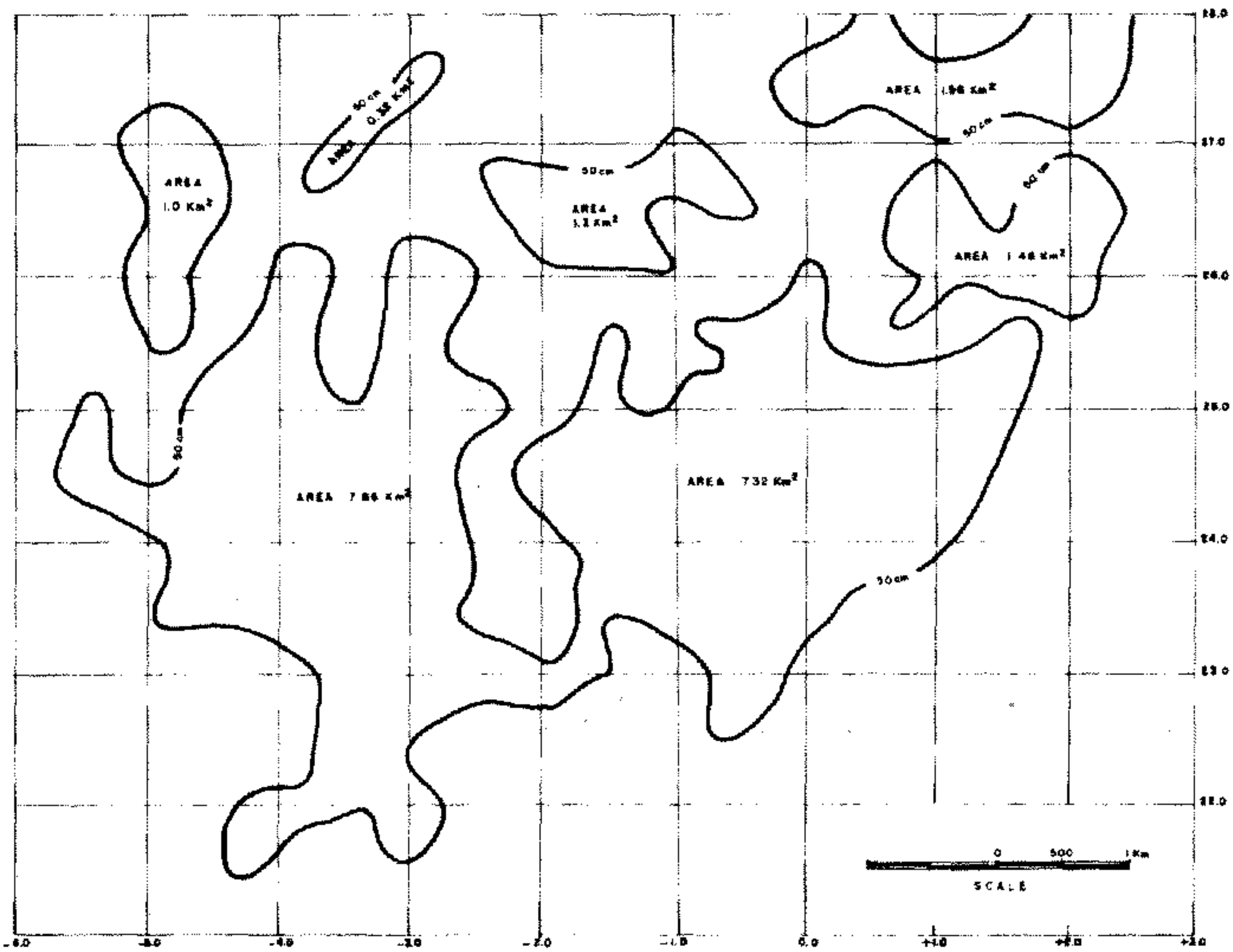

Figure 4. Clay isopachous lines to two meters depth showing aggregate clay thickness of at least 50 cm overall (over 21 km^2 good quality clay).

drop in a non-leaking evaporation pan using a similar brine and installed at the pond area. As previously indicated the pan and pond evaporation rates differ. Consequently, to estimate the pond evaporation and hence its leakage the 0.71 scale factor generated by experience was used. An average permeability of 2.7×10^{-7} cm/sec was calculated at the pond site (assuming a 50-cm thickness of good clay).

SOLAR POND DESIGN

Solar Pond System

To recover the potash salts from the Salar de Atacama brines it is necessary to evaporate high volumes of brine in large ponds. The solar evaporation ponds for a potash project will be sited in the area of good quality clays already described (over 21 km^2 with permeabilities less than 2.5×10^{-7} cm/sec). This area has an almost zero gradient (0.4 m in 1000 m). The existing salt crust over the clays will be used as a protective cap. Experience has shown that removal of this salt may result in damage of the underlying highly plastic clays.

The pond system will consist of three groups of flow-through ponds corresponding to the three distinct evaporation fields, halite, sylvinite and mixed sulfates. The number of ponds in each of the three groups is controlled by a combination of being able to vary the area in accordance with changes in evaporation rates and production needs, and to maintain an adequate evaporation area in service during harvesting periods. The sylvinite and sulfate ponds will be harvested for the plant feed, and the halite ponds to maintain the pond level. Brine transfer within each group of ponds will be by gravity flow and pumping.

Pond Construction

In the clay area, pond construction will consist solely of constructing the dikes. All exterior dikes will contain a center cutoff trench filled with compacted clay to the full dike height and extending to the bottom of the basal clay layer (Figure 5). Clay compaction on the trenches will be done by self-propelled compactors. Interior dikes will not be cored, as leakage will be only a minor amount of normal flow and probably will be negligible after several years of operation. The proposed dimensions for the dikes are shown in Table 3. Material for the exterior and interior dikes will be obtained from a borrow pit located about 18 kilometers west of the solar ponds. This material will be loaded into trucks by front-end loaders and hauled to the pond area. The center cutoff trench will be filled with good quality clays obtained from borrow pits located on small isolated areas in the same clay pond area.

The basal clay layer will be at least 50 cm thick. A cap of 30 cm of halite and/or sylvinite will be built up on top of the in situ clay to form a strong protective base, together with the existing salt crust.

TABLE 3

Dike Dimensions

Total height (H)	2.00 m
Trench width (t)	0.85 m
Trench depth (d)	2.70 m
External dike width (W_e)	4.00 m
Internal dike width (W_i)	3.00 m
Slope (external)	2/1
Slope (internal)	3/1

Pond Sizing

The pond area required to evaporate water from brines in order to produce the desired tonnage of salts is given by the equation

$$A = \frac{\text{(Evaporated water)}}{\text{(Evaporation rate) (Water density)}} = \frac{W}{e_v\, d_w}\ (\text{km}^2). \tag{1}$$

To calculate the evaporated water it is necessary to write down a material balance for each pond.

$$\begin{pmatrix}\text{Entering}\\ \text{brine}\end{pmatrix} = \begin{pmatrix}\text{Leaving}\\ \text{brine}\end{pmatrix} + \begin{pmatrix}\text{Evaporated}\\ \text{water}\end{pmatrix} + \begin{pmatrix}\text{Entrained}\\ \text{brine}\end{pmatrix} + \begin{pmatrix}\text{Leaked}\\ \text{brine}\end{pmatrix} + \begin{pmatrix}\text{Crystallized}\\ \text{salts}\end{pmatrix} \tag{2}$$

or in symbols,

$$B_i = B_0 + W + E + L + S. \tag{3}$$

The material balance for each component (j) is given by

$$X_{j,i}B_i = X_{j,0}B_0 + X_{j,E}E + X_{j,L}L + X_{j,S}S \tag{4}$$

where X_j is the composition (in weight per cent) of each component in the brines and salts. It is assumed that the

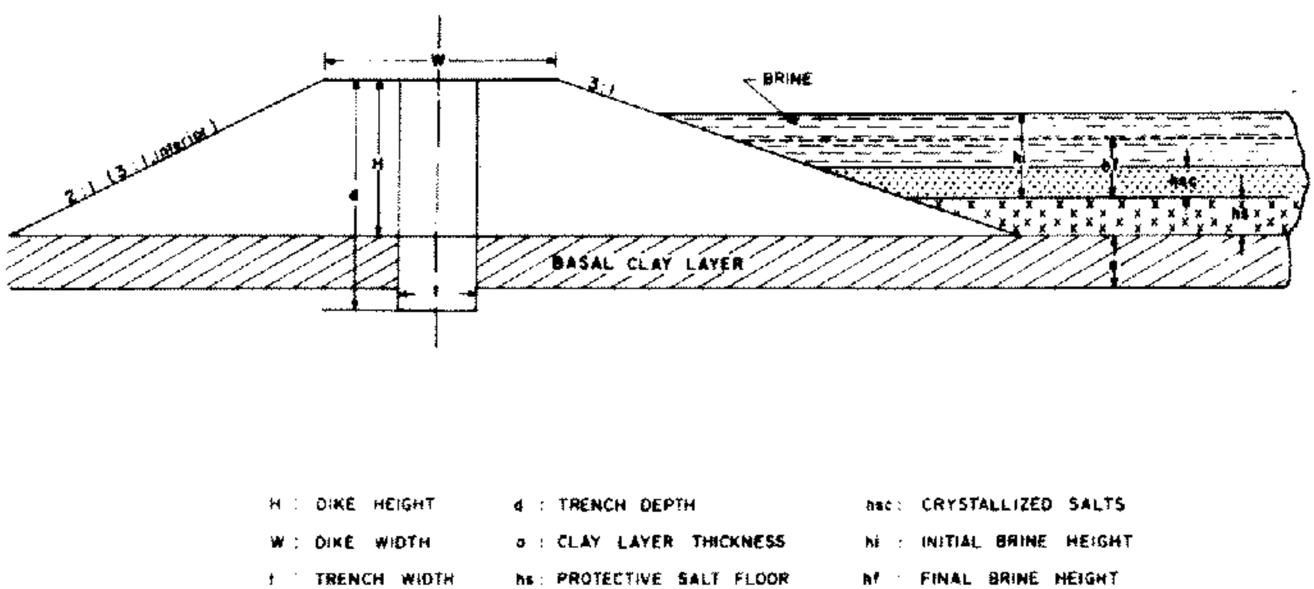

Figure 5. Solar pond cross sections.

composition of the entrainment is the same as that of the leakage, and is calculated as

$$X_{j,E} = X_{j,L} = (X_{j,i} + 2X_{j,0})/3. \qquad (5)$$

Using the phase chemistry information it is possible to define for each evaporation stage a crystallization coefficient (Parada-Frederick, 1982) as

$$c = \frac{W}{S}. \qquad (6)$$

This coefficient c is different for each stage and also changes from summer to winter, as shown in Table 4.

With the relationship given by Eq. 6, it is possible to express the evaporated water in terms of the total crystallized salts.

$$W = cS \qquad (7)$$

The brine occluded in the salts can be evaluated if their porosity is known. Because the porosity of salts crystallized in commercial ponds is not known, it was assumed for halite and sylvinite salts a 15% impregnation, and 25% for the sulfate salts. Therefore, the entrainment can be expressed also in terms of the crystallized salts.

$$E = pS \qquad (8)$$

where $p = 0.15$ for halite and sylvinite salts, and $p = 0.25$ for sulfate salts.

The solar clay ponds are not tight enough and brine will leak through it. To estimate the losses of brine produced by seepage we will use the D'Arcy's equation

$$L = kAd_L \frac{\Delta H}{a} \qquad (9)$$

where

- k = permeability of clay, (m/sec)
- A = pond bottom area (m^2)
- d_L = density of brine, (ton/m^3)
- a = clay layer thickness (m)
- ΔH = piezometric height; pressure difference across the width of the clay layer, (m)

and

$$\Delta H = a + h_s + h$$

where

- h_s = protective salt floor (0.30 m) (10)
- h = average brine height over the protective salt floor

To simplify the mathematics, a batch model was assumed for the pond operation. Initially a given pond is filled with brine up to 0.30 m. When the brine in the pond has reached the desired final composition, it is pumped to another pond and replenished with the same initial brine up to the same height on top the crystallized salts. Through the whole evaporation process salts have been precipitating on the bottom of the pond, leaving at the end of the evaporation a salt layer of crystallized salts (h_{sc}). The average brine height in the pond (h) will be calculated as an average between the initial (h_i) and the final (h_f) brine height (Figure 5)

$$h = \frac{h_i + h_f}{2} \qquad (11)$$

and

$$h_f = h_b + h_{sc}. \qquad (12)$$

It is assumed that all the salts are porous,
If we define

- h_w = equivalent height of evaporated water
- h_L = equivalent height of leaked brine

then,

$$h_b = h_i - h_w - h_L - h_{sc} \qquad (13)$$

also,

$$h_{sc} = \frac{h_w d_w}{c d_s} \qquad (14)$$

d_s = density of salt

$$h_L = \frac{L}{Ad_L} \frac{h_w}{e_v}. \qquad (15)$$

Substituting equations (13), (12) and (11) into (10) we obtain

$$\Delta H = a + h_s + h_i - (h_L + h_w)/2. \qquad (16)$$

Substituting equations (15) and (16) into equation (9) and rearranging, h_L is defined with a relationship like this:

$$h_L = \frac{2\alpha h_w (\beta - \gamma h_w)}{1 + \alpha h_w}. \qquad (17)$$

TABLE 4

Crystallization Coefficients

	Summer	Winter
Halite	2.94	3.17
Sylvinite	2.41	1.85
Sulfate	1.65	2.19

Making a material balance in a pond for a given batch we get (assuming bottom size equal to evaporation area)

$$A h_i d_i = A [h_b d_b + h_w d_w + h_L d_L + h_{sc} d_s]. \quad (18)$$

Substituting h_{sc} from equation (14) and h_b by equation (13) and rearranging, we have a simplified equation for h_L

$$h_L = \delta - \mu h_w. \quad (19)$$

Solving simultaneously equations (17) and (19) we can obtain the values of h_w and h_L for each batch.

The harvesting will be done when a layer of 0.30 m of salts is formed on top of the protective salt floor.

The number of batches necessary to obtain this harvesting layer (H_c) is given by

$$H_c = \sum_{n=1}^{N} h_{sc,n} = 0.30\,\text{m} \quad (20)$$

where N is the number of batches.
The total time (T) required to form H_c,

$$T = \sum_{n=1}^{N} t_n \quad (21)$$

where

$$t_n = \left(\frac{h_w}{e_v} \right)_n. \quad (22)$$

If we define

$$l = \frac{\sum_{n=1}^{N} h_{L,n}}{\sum_{n=1}^{N} t_n} \quad (23)$$

Then, the leakage in the pond can be expressed as

$$L = A l\, d_L \quad (24)$$

and for a period of time T_v, the total leakage is given by

$$L_{tot} = L T_v \quad (25)$$

where T_v = total evaporation time; 7 months for "summer" and 5 months for "winter."
Substituting equations (1) and (7) in equation (24) we can express leakage in terms of the crystallized salts

$$L = m\, S. \quad (26)$$

Therefore, the total material balance can be expressed in the form

$$B_i = B_0 + (1 + c + p + m)\, S. \quad (27)$$

The area of the sylvinite ponds will be the first to be calculated. The total tonnage of salts crystallized in these ponds can be determined with the desired potassium chloride production (520,000 tons per year), the chemical plant yield (86%) and the composition of the sylvinite salts. The chemical composition of the salts is slightly different in summer in comparison with winter, and this must be taken into account in the calculations.

Through a trial and error method and starting with summer conditions, the sylvinite ponds area can be calculated. Then, with the entering and leaving brines of the sylvinite ponds, the areas of halite and sulfate ponds are determined, respectively.

Because there is one total material balance and j equation per component, an average value for each mass flow should be calculated. The areas calculated (theoretical) with this model are presented in Table 5. These areas should be increased to add both a contingency and compensation for areas out of service during harvesting.

TABLE 5

Calculated evaporation pond areas

Pond	Area (km^2)
Halite	7.06
Sylvinite	3.38
Sulfates	1.57

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