An Approach to Process and Quality Control Relevant to Solar Salt Field Operations in the Northwest of Western Australia

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ABSTRACT

The principles and parameters behind the design and field layout of the Dampier solar salt field were based on the theoretical and empirical work of C.W. Bonython. A resume in terms of the total field design is given and the utilization of these design considerations as a basis for process control, treating the operation as a continuous flow concept to achieve optimum control and efficiency is described.

As distinct from the ideal, the practical aspects which must be considered for efficient and effective field control in an area where relatively wide day to day variations in climatic conditions are experienced, are also noted, and measures to accommodate these conditions are duly described.

Features of the washing plant and the complementary design considerations of the field and washing plant which can affect product quality are noted and the operational procedures adopted to meet the high product quality requirements of the customers are described.

INTRODUCTION

The salt field at Dampier was established in 1970, at a nominal design production level of 2.4 million tons per annum to meet the growing demand for industrial grade salt in Japan and South East Asia. The site, and its location (Fig. 1) have all the necessary attributes for a successful solar salt operation, including proximity to the market. However, the one notable disadvantage is that the area is subject to the influence of cyclones during the summer period with an average frequency of two to three times per year.

While these phenomena have relatively little influence on the process and its operation, apart from interruption due to associated rainfall, it was necessary to design all civil, mechanical and structrual components to withstand cyclonic winds in order to ensure the integrity of the field and the continuity of operations. The premium for this is estimated at 25% of the initial capital cost of the field.

Design was undertaken in 1965 at which time no meteorological information was available for the Dampier area. Therefore the limited basic meteorological data from a number of isolated settlements in the region was accepted, while the remaining unknown parameters of necessity were calculated by the use of a number of theoretical and empirical relationships.

The paper summarizes these relationships and the overall design method used, together with the operational procedures subsequently adopted. It emphasizes the most significant aspects of operations which can affect product quality, including those with relatively marginal influence, due to the significant market advantage currently held by high quality salt.

Because of the market advantage, operational, material handling and general quality control procedures have been established to achieve the necessary requirements within all reasonable practical and economic limits. Some of these procedures are also described in the paper.

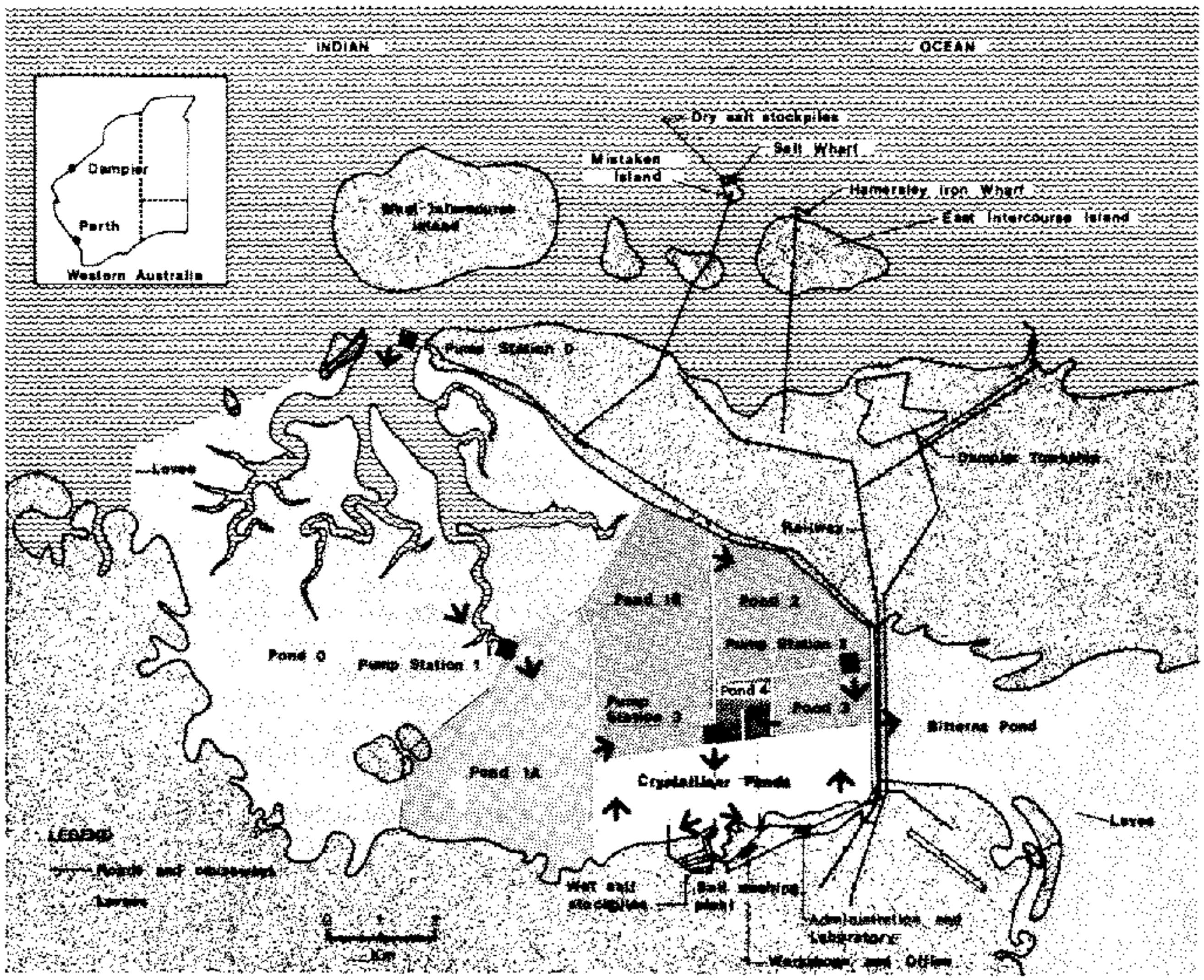

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Figure 1. Schematic diagram of field layout, tidal flats etc. with an insert map of Western Australia showing location of Dampier.

SALT FIELD DESIGN AND LAYOUT

Evaporation. The general expressions used to estimate the fresh water (pan) evaporation rate and the rate of evaporation in brine ponds are described in Bonython's treatise on solar evaporation (Bonython, 1966). Together with other relationships summarized below, these have formed the basis of the Dampier design. All are quoted in their original form utilizing corresponding source units.

A form of the basic equation for evaporation rate E is:

$$E = \frac{2h}{L}(p_w - p_a)\ \text{cm/hr} \qquad (1)$$

where h = heat transfer coefficient; cal/cm^2/hr/°C
L = latent heat vaporization; cal/gm
p_w = vapor pressure at the water surface; mm of merc.
p_a = partial pressure of water vapor in the air; mm of merc.

Figure 2 shows a relationship compiled from the results of a number of separate investigations (Bonython 1966) and provides a convenient vehicle for estimation of the mass transfer coefficient k in relation to the down-wind dimension of a body of water. Thus, for application in solving the

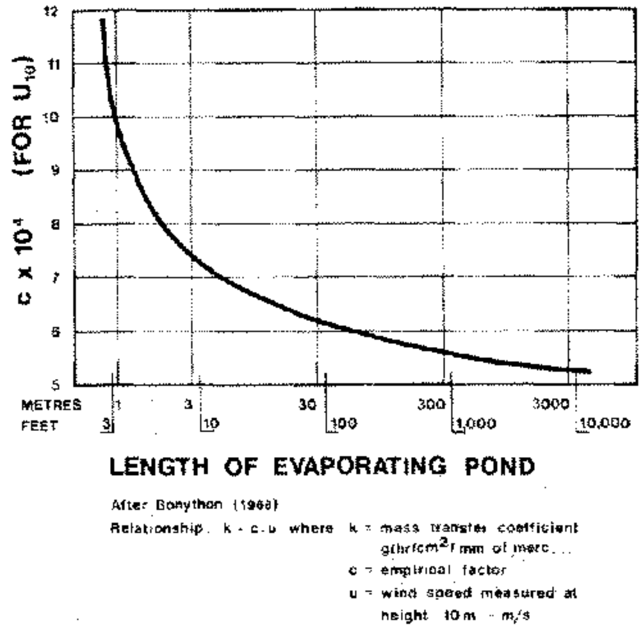


Figure 2. Effect of pond size on transfer coefficient.

relevant equations, h can be estimated by the standard hygrometric relationship:

$$\frac{h}{kL} = 0.5 \qquad (2)$$

where k = mass transfer coefficient, gm/cm²/hr/mm of merc.

Q_a, the Nett Gain of Radiant Energy by a water surface at air temperature, was derived by the following equation which in its final form is a slightly modified version of the Penman equation (Penman, 1948).

Neglecting the minor effects of Reflected Long-Wave Radiation, a modified form of the general expression is:

$$Q_a = (I_o - I_R) - (R_w - R_a) \text{ cal/cm}^2\text{/hr} \qquad (3)$$

where I_o = incoming short-wave radiation
I_R = reflected insolation at the water surface
R_w = outgoing long-wave radiation
R_a = incoming long-wave radiation

Incoming short-wave radiation (I_o). I_o was estimated using the form of relationship attributable to Angstrom:

$$I_o/I_A = a + b\, n/N \qquad (4)$$

where I_A = total radiation received if the atmosphere were perfectly transparent
n = actual duration of bright sunshine received
N = maximum possible duration of bright sunshine
a & b are constants

The values of Angot (Brunt, 1939) were used for I_A while the values for a and b were taken as 0.3 and 0.5 respectively; these having been determined for Adelaide, South Australia. (Black, Bonython and Prescott, 1954).

Nett outgoing long-wave radiation ($R_w - R_a$). This was obtained by use of the relationship for Nett Back Long-Wave Radiation for a Cloudless Sky as derived during the Lake Hefner studies in the U.S.A. (Anderson, 1952) with the factor for control of this parameter due to cloudiness retained as in the Penman equation, to give:

$$(R_w - R_a) = 0.97\sigma T^4 (0.32 - 0.042\sqrt{p_a})(0.1 + 0.9n/N) \qquad (5)$$

where σ = Stefans' Constant; cal/cm²/sec/°K⁴
and T = air temperature; °K

Taking I_R as 4% of I_o and substituting equations (4) and (5) in equation (3) gives:

$$Q_a = 0.96\, I_A (0.3 + 0.5\, n/N) - 0.97\sigma T^4 (0.32 - 0.042\sqrt{p_a})(0.1 + 0.9n/N) \qquad (6)$$

Estimation of p_b, the vapor pressure of brine in a pond at the salting point was obtained by graphical solution of the modified Ferguson equation (Ferguson, 1952):

$$2p_b + \theta_b (1 + r/h) = Q_a/h + 2\, p_a + \theta_a (1 + r/h) \qquad (7)$$

where θ_b = brine (or water) temperature; °C
θ_a = air temperature; °C
r = emission coefficient for black body radiation; cal/cm²/hr

This expression, in the simplified form, which neglects the correction factor for radiation, was used to determine p_w, as applied to fresh water evaporation.

The general expressions listed above enabled the calculation of the two parameters.

E_e—Gross Evaporation Rate (G.E.R.) for Fresh Water in a Standard Evaporimeter
E_b—Gross Evaporation Rate for Brine at the Salting in large ponds.

The relationship demonstrating the extent of divergence between calculated results and actual evaporation of brines

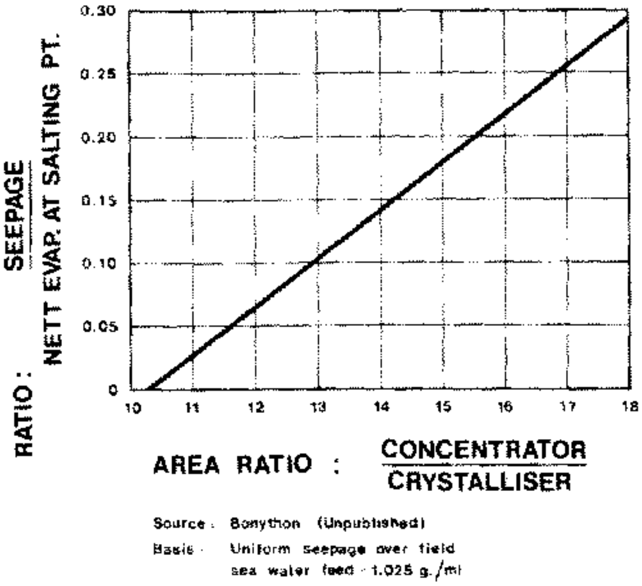


Figure 3. Relationship between bond area ratio and relative seepage.

(Bonython 1966, Fig. 3) was used to arrive at a "corrected" gross evaporation rate for brine in ponds at the salting point E_{bc}.

Such calculations were used to determine the areas of ponds in the initial design of the salt field. A method is described later for short-term control of pond operation based on an empirical relationship between pond evaporation derived as above and measured pan evaporation of fresh water.

AREA RATIOS AND POND LAYOUT

Concentration/crystallizer area requirement. Crystallizer area appropriate to the desired production level was determined on the assumption of complete absorption of insolation i.e. no losses due to reflection from deposited salts, and operating limits of 1.216 to 1.250 gm/ml at 20°C.

The estimation of the area requirements for concentration ponds, necessary to provide a sufficient supply of saturated brine to unit area of crystallizing pond, was part of a rigorous theoretical study undertaken to determine a general approach to salt field design for a range of conditions of evaporation, seepage, rainfall and seawater feed concentration, (Myers and Bonython, 1958).

This work assumed a progressive reduction in seepage as the brine proceeds through the field, this being an observed feature of a particular, established salt field of elongated form adjacent to a shoreline. The new, more compact Dampier salt field was expected to have a reasonably uniform seepage rate over its pond areas. Criteria were adopted for Dampier, including a selected seawater feed concentration and various uniform seepage rates, giving rise to a graph relating concentrating/crystallizing area ratio to seepage rate—see Figure 3 (Bonython, unpublished, personal communication).

To allow for the uncertainty of environmental factors, namely rainfall, runoff and seepage, a margin for safety of 5% was adopted to give a theoretical area ratio of 12.9 to 1. As weather conditions at Dampier permit continuous operations throughout the full year, the theoretical crystallizer area had to be increased to account for "down time" associated with draining, harvesting and refilling the respective areas.

The design was also based on the use of dye in the crystallizing brines for the nominal production rate to cut radiation reflection losses. However, with the current, lower levels of production, dye is not used and an additional 15% more crystallizer area is used to account for the reflection losses.

Pond layout. The location of the crystallizers was determined by the features of the area which was very even requiring little work for preparation, but was of sufficient slope to allow gravity flow from one crystallizer in a series to the next, while still maintaining the same brine level in each. Furthermore, the different levels in successive ponds facilitated ready and rapid drainage into the downstream pond prior to harvest, the sequence of harvest being in the reverse direction to brine flow.

Layout of the crystallizers as a number of parallel rows in series was chosen primarily because of the better potential for *higher quality* and better *quality control* with lower overall washing losses, and with minimum harvest "down time" as a further important consideration. Subdivision within the series was based on equal concentration drop across each pond.

The concentration area is a six pond system with a calculated successive reduction in the area of each pond. The layout was determined mainly by the topography.

Further pond subdivision, although possibly desirable, was avoided because of the higher costs involved in meeting the structural requirements necessary for the cyclone conditions.

PROCESS OPERATION

General. In describing the brine movement control as practiced at Dampier, it is relevant to detail some features of the weather. Figure 4 shows the average monthly pan freshwater evaporation levels and rainfall as recorded over 8 years of operations and more particularly, in relation to brine movements, a calculated average monthly value of E_{bc}, the gross evaporation rate for brine in the ponds at the salting point.

Rainfall is unpredictable in terms of frequency, but usually occurs in intense falls (75–150 mm) of short duration (3–4 days). It is a common occurrence within the monthly

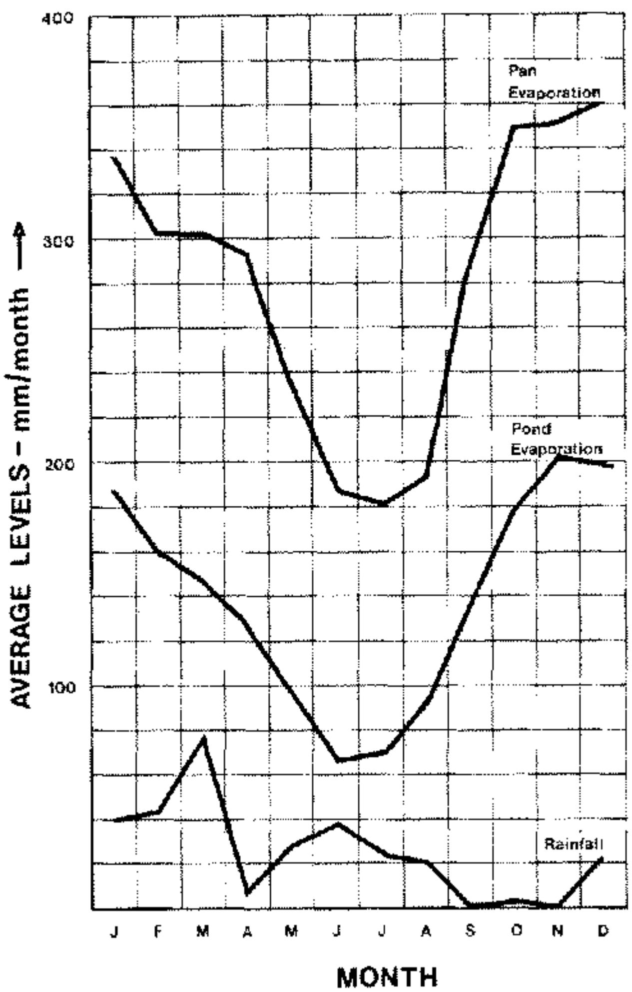


Figure 4. Monthly average variation for pan evaporation, pond evaporation and rainfall.

averages for pan evaporation to record changes in readings of to ± 25% of the mean, with extremes being achieved on successive days. This is a summer time feature and occurs when there is a shift of the two prevailing winds from the westerlies (off the ocean) to the easterlies, which bring dry hot air from the continental interior. Pan evaporation rates have varied from 10 mm to 17' mm on consecutive days due to this cause.

Control reference. In discussing process control it is important to note that the control reference used is the Australian sunken pan, which has been replaced within the Australian Meteorological Network by the International Class 'A' pan. The former is 910 mm diameter × 910 mm deep with a water filled annular ring of width 152 mm, the whole assembly being set in the ground. Retention of this unit in Dampier Salt as a control reference device is due to the fact that: a) The sunken pan situation is believed to reflect pond conditions more closely than above ground evaporimeters, and b) some of the field design criteria relating to fresh water evaporation rates have been largely developed around this style of evaporimeter, or other insulated units.

By applying actual meteorological data in the evaporation equations detailed earlier it has been possible to calculate pond evaporation rates which compare favorably with field observations, adding confidence to the theory. However, when the above data are used in the equations to calculate pan evaporation, the derived rates are significantly lower than the observed ones, in accordance with a tendency reported previously (Bonython, 1950).

This divergence from the theoretical is due without doubt to a number of factors associated with the configuration of the instrument, but is not constant. Similarly, the relationship between the pan and pond evaporation is also not constant, although this is predicted by the theory as being a function of the prevailing meteorological conditions.

The philosophy evolving from this, to achieve the best (but not ideal) means for field control, is the use of average calculated values for E_{bc} to give the most probable level at any given time and to define a further control parameter, the ratio E_{bc}/E_e for each month, recognizing that the pan evaporimeter does not define absolute fresh water rates but rather indicates changes from day to day.

Control considerations. Except in times of rainfall, brine movements through all parts of the field are continuous to meet the following requirements.

1. *Constant pond level:* All ponds are retained at the lowest possible operating level to minimize damage to pond levees in times of cyclones. At the same time, variations to brine level are avoided to prevent disturbing the density profile throughout the field. Changes in level also unnecessarily complicate control, particularly at weirs, where control information has been derived for constant head differential between respective ponds.

   Excessive brine depths can significantly reduce the sensitivity of shallow ponds in restoring design density, particularly for those ponds operating near the salting point, whereas relatively small changes from the optimum depth in the crystallizers can have adverse effects on the characteristics of the deposited salt.

2. *Constant pond discharge density:* This requirement is complementary to (1) and is important to ensure that brine is available to the crystallizers at, or near the salting point (1.216 g/ml at 20°C) with the major considerations for this is as follows.
   a. If the density is too high. Rapid salting of the maiden brine transfer pumps occurs resulting in reduction of performance or pump seizure with possible mechanical damage. In the extreme, failure of the pumps due to salting can result in starvation of the crystallizers, with a consequential increase in levels of the final concentrating ponds.

b. If the density is too low. Higher calcium sulphate deposition in the series 1 crystallizers occurs which can have significant adverse effects on Ca^{++} levels of product salt.

The nominal crystallizer feed density is within the range 1.213–1.218 gm/ml at 20°C; levels higher than 1.216 seem to be possible with the high brine temperatures. In summer it is essential to operate towards or below the lower limit of density to ensure freedom from salting.

3. *Feed channel hydraulic profile:* Dependent on both (a) and (b) above, continuous and constant flow from the maiden brine pump station is important, to retain the hydraulic profile of the feed channel which services 9 crystallizer rows, where the extreme distance from the pump station is 4,300 meters. Achieving this requirement can minimize labor costs in weir adjustments while still retaining the correct feed rates to each row.

Apart from the quality considerations, the problems associated with pumping maiden brine which has commenced salting and particularly under the variable conditions in summer cannot be understated in terms of the significant cost penalties involved, mainly in terms of labor. Thus to meet this and the other control requirements, continuous flowsheet operation relative to the demands of the weather is necessary.

This approach of flowsheet operation as compared with intermittent brine movements has of course the advantage of reducing installed plant in terms of pumps, electric motors, weirs and bridges to reasonable practical minimum sizes with a consequent reduction of capital cost.

Field control. Flow requirements at each transfer point in the field have been calculated by preparing a series of flowsheets for a range of fresh water (pan) evaporation rates. As noted above, the relationship between pan evaporation rates and evaporation in the pond is variable and flow rate requirements relative to the pan evaporation must be adjusted according to the calculated average seasonal variations in the ratio E_{bc}/E_e. A typical set of curves detailing the brine movement requirements at one such transfer point is shown in Figure 5.

Brine movement programs are set in advance for the following week by assuming a fresh water evaporation rate based on the results of the preceding three days. An arbitrary allowance, up or down, is made depending on the difference of the assumed level from the monthly mean and/or the period of the year. The commencement time of any operating week corresponds with the time of the daily evaporation readings.

The evaporation level assumed is reviewed every second day, relative to achieved evaporation, and if necessary proportional adjustments up or down are made to be taken up during the remainder of the operating week. Any surplus

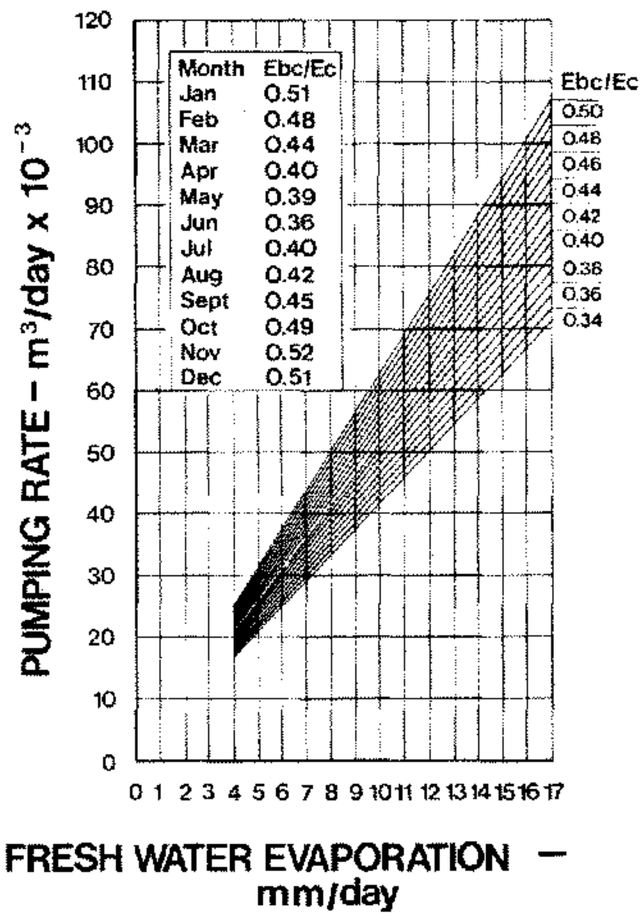


Figure 5. Brine transfer point control sheet.

or deficit in pumping due to over-or-under estimation of evaporation levels is carried forward to the next operating week and the incremental amount is taken up in the first two days of the next week.

To monitor the process, laboratory personnel take daily readings of concentration pond levels from level gauges, located at 3 points in each pond to obviate the effects of wind, and daily readings of pond exit densities. These two readings are essential to provide information on a) the accuracy of the brine programs; b) the correct program implementation; c) trends in the system; d) possible brine segregation in the ponds; and e) accuracy of the ratio E_{bc}/E_e.

Crystallizer exit densities and brine depths, also read from gauges are taken every second day for the same reasons defined above. Because of the importance placed on crystallizer brine depths, actual physical measurements of these are made once per month. This is necessary to adjust for the effect of salt growth which averages 25 mm/month.

The concentrated nature of the intermittent rainfall as described, usually necessitates temporary closure of the field. All pumps are turned off and weirs sealed, until just prior to restoration of programmed density, at which time pumping at the maiden brine pump station commences at rates well below flow sheet requirement in order to reestablish the density profile across the pond. Pumping is slowly returned to normal, following this sequence back through the field. Establishment of the density profile before operating densities are achieved is necessary in order to avoid the difficulties of "salting".

WASHING, QUALITY AND QUALITY CONTROL

General. While there is no formal quality specification other than the requirement for a minimum NaCl content of 96% wt. (wet basis), a consistent and high quality salt is sought within all practical and economic limits, with a typical NaCl content of 96.5–97.2% wt. on a wet basis, or 99.6–99.7% wt. on a dry basis.

To achieve this objective with minimum losses, there are a number of contributing factors to be considered, the most important ones are 1) crystallizers. The appropriate brine operating depth together with the series configuration and flexibility derived from this. 2) Wash Plant. The selection of the optimum wire belt mesh appropriate to the harvest salt, and suitable flows of wash brine.

Crystallizers. Good brine control is not only important for maintaining the correct feed density in order to minimize Ca^{++} levels and to discharge at the selected bitterns density of 1.250 g/ml, but also, because of the sensitivity of deposited salt crystal size to operating depth. It is desirable therefore to maintain the brine depth at the correct level to produce crystallized salt of satisfactory characteristics to minimize operational difficulties and achieve successful washing. As illustration of the effect of brine depth, taking the two extreme situations of, say, ± 10 cm. from the selected operating depth, the consequences listed in Table 1 have been observed.

The appropriate operating depth for achieving the requisite balance between the two extremes has been established by experience and is modified slightly according to the season.

The benefits of series crystallizers over parallel layout are well known and will not be dealt with in any great detail

TABLE 1

Operating Depth Effects

Crystallized Salt	Features	Consequences
(A) Operating Depth Too Great.		
Fine Salt	High Moisture content to wash plant	Higher washing losses due to adsorbed brine
		Inefficient washing with screen blinding resulting in higher Ca^{++} levels
		Higher moisture content after stockpile draining
	Higher drainage in transit due to higher initial levels of moisture	Higher road maintenance costs
Low Bulk Density	Lower load bearing capacity of salt crust in relation to harvesting plant	Potential for crystallizer pavement failure Reduced harvesting rate
(B) Operating Depth Too Shallow. *(Neglecting effect of higher reflection losses and/or dye costs, if used.)*		
Crystallized Salt	**Features**	**Consequences**
Coarser Salt	Relatively low moisture content to wash plant	Lower washing losses
		Higher washing efficiency with good quality product
High Bulk	High load bearing capacity of salt crust	No pavement failure problems
	Salt extremely hard	Ripping to permit havesting increases with consequent severe cost penalty in terms of time and equipment maintenance
		Reduced harvesting rate

TABLE 2

Series Crystallizers.

(1) Series	(2) Theoretical Operating SG of Brine gm/ml	(3) Theoretical Mg^{++} of Brine (gm/ml)	(4) Occluded Ca^{++} in Salt —% wt.	(5) Occluded Mg^{++} in Salt —% wt.	(6)* Actual Washplant Feed Ca^{++}—% wt.	(7)* Actual Washplant Product Ca^{++}—% wt.	(8)** Theoretical Washing Losses of NaCl—% wt.
1	1.224	18.7	0.006	0.003	0.21–0.24	0.045	3.4
2	1.235	27.2	0.005	0.004	0.16–0.18	0.034	6.3
3	1.250	39.1	0.004	0.006	0.13–0.15	0.027	10.4
Weighted Average	1.233	27.1	0.005	0.004	0.19	0.037	6.3

*Corrected for adsorbed mother liquor.

**Based on 7% M/C (Dry Basis) as wash-plant feed.

other than to note that the salt produced in the respective ponds show different chemical characteristics, with higher calcium impurity and lower magnesium levels in the first pond of the series, and with the converse applying to the last pond. This appears to be true of both occluded and adsorbed Ca^{++} and Mg^{++} impurities. The different characteristics of course require different wash plant treatments in order to achieve a constant quality. However, with a constant Ca^{++} removal efficiency of 80%, different quality product salt comes from the different crystallizers, giving scope for selective blending. Table 2 summarizes some of the relevant features of series crystallizer operation at Dampier.

Wash plant and stockpile. The wash plant has been designed on the conventional principle of a high volume of saturated brine wash over the travelling woven wire screen belts for the removal of the solid impurities (insolubles and $CaSO_4$). Control of the dissolved impurities, specifically the magnesium salts associated with adsorbed mother liquor, is achieved by dilution with a low magnesium content brine and subsequent dewatering.

Six wire wash belts are presently installed, each with a capacity in excess of 150 TPH, depending on the particle size of the feed. These units are complemented by an hydraulic cyclone/fine wire mesh belt recovery system for the fines which pass through the larger mesh primary belts.

As in most other large scale plants, no attempt is made to mechanically dewater the washed salt, this being achieved by drainage during an adequate residence time in the stockpile. At Dampier, 6 weeks draining in the stockpile produces salt of a satisfactory moisture content, and in consequence, a satisfactory magnesium content of the drained salt, provided the salt particle size is satisfactory.

Water as a process material for control of dissolved impurities is impractical in an arid area such as Dampier. With the actual location of the plant, seawater usage for this purpose is also precluded and of necessity, brine from one of the concentrating ponds is used. Because of its relatively high Mg^{++} level (4.4 gm/l) considerably higher process flows are required for any given plant throughput than would be the case with either fresh or seawater. At the same time this produces marginally higher washing losses to achieve the same quality, due to the larger volumes of wash brine required.

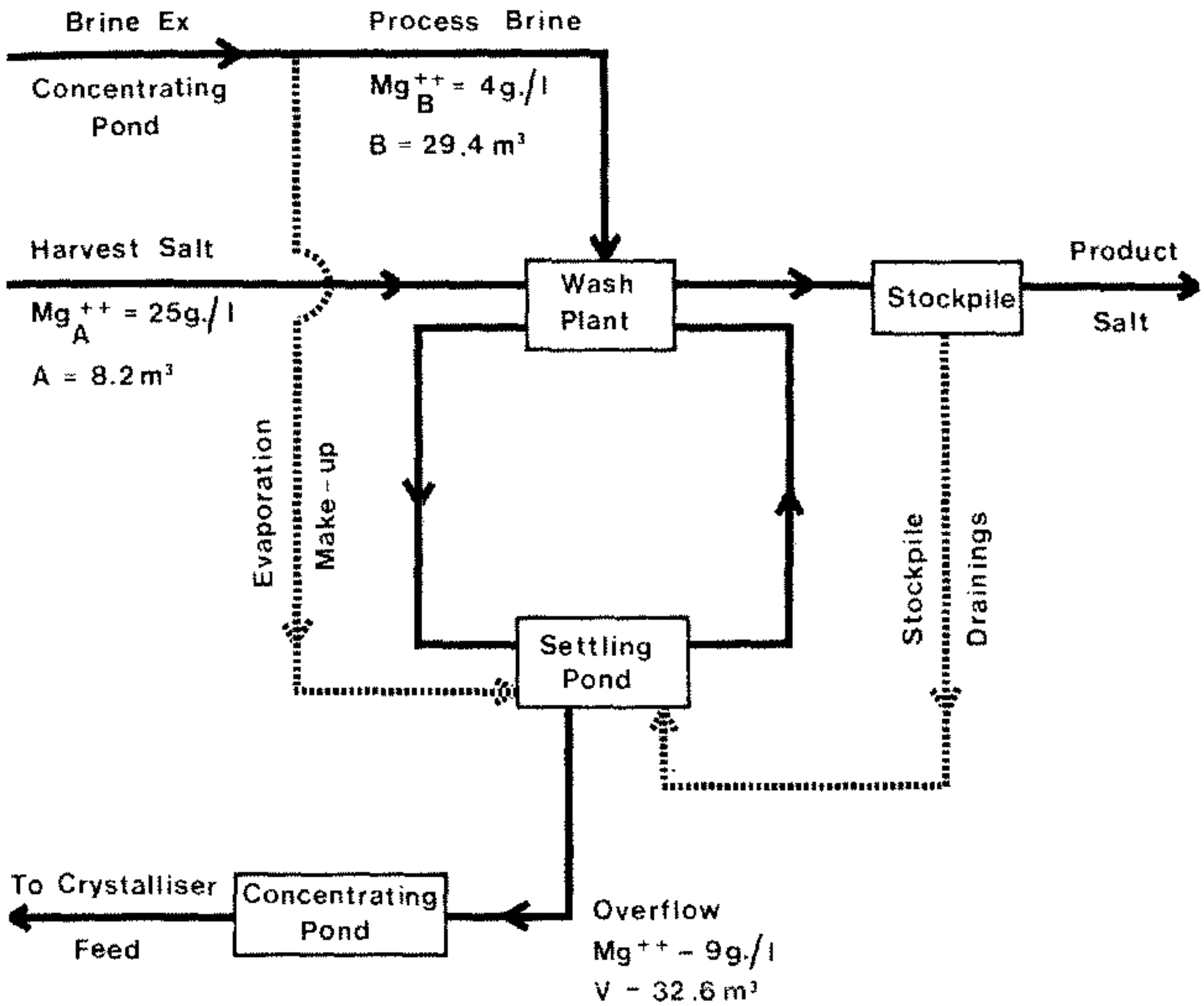
The quantity of process brine used for dilution is a function of the volume of adsorbed brine on the harvest salt and its corresponding magnesium concentration. Addition of this dilution brine is at a rate designed to maintain a constant Mg^{++} concentration in the high volume saturated brine wash circuit. This concentration is selected on the basis of achieving a magnesium content of 0.03–0.04 wt. of the washed salt after it drains in the stockpile to below 3% wt. moisture.

It is also essential to provide sufficient additional process brine to compensate for evaporation in the settling pond so that the correct Mg^{++} concentration is maintained. As the volume required for this is a function of the weather, it is independent of plant washing rate, and the brine used bypasses the plant and feeds directly to the settling pond. After compensation for evaporation, this brine has a small potential for salt solution and further minor losses result. Figure 6 shows a schematic representation of the brine flows used in the Dampier plant based on a feed rate of 100 tons per hour of harvested salt which was deposited under the weighted average crystallizer brine conditions.

A control nomograph defining dilution brine requirements (Fig. 7) is used to assist plant personnel in maintaining constant salt quality with minimum losses for a range of conditions which are introduced through differences in harvest salt properties, variation in the harvest salt moisture and possible variation in the composition of the dilution brine.

The basis of the nomograph is the simple proportional relationship:

$$(A \times Mg_A) + \frac{(B \times Mg_B)}{1.11} = (A + B) \times 9 \qquad (8)$$



Note. 1. Based on 100 T.P.H. pure Na Cl.
2. Weighted mean crystalliser condition.
3. Moisture of harvest and washed salt - 7 %.
4. Major flows only.

Figure 6. Schematic of brine flows. Wash plant.

where A	Cu.m/unit time of brine adsorbed with harvest salt (To wash plant)
$Mg_A = M_x^{++}$	Concentration of adsorbed liquor, gm/liter.
B =	Cu.m/unit time of dilution brine.
$Mg_B = Mg^{++}$	Concentration of dilution brine, gm/liter.
Factor 1.11	This allows for the volume increase of the dilution brine with salt dissolution to saturation.

A small subsidiary laboratory is annexed to the washing plant where hourly analysis of feed and discharge of salt quality and daily analysis of the process brines is undertaken. This provides data to indicate whether selective harvesting is necessary, whether there are changes in harvest salt impurity levels or moisture content, plant washing efficiency and other associated quality control considerations.

With this control and monitoring, a long stockpile configuration and the aid of the travelling stacker it is possible to exercise full grade control both in stacking and reclaiming.

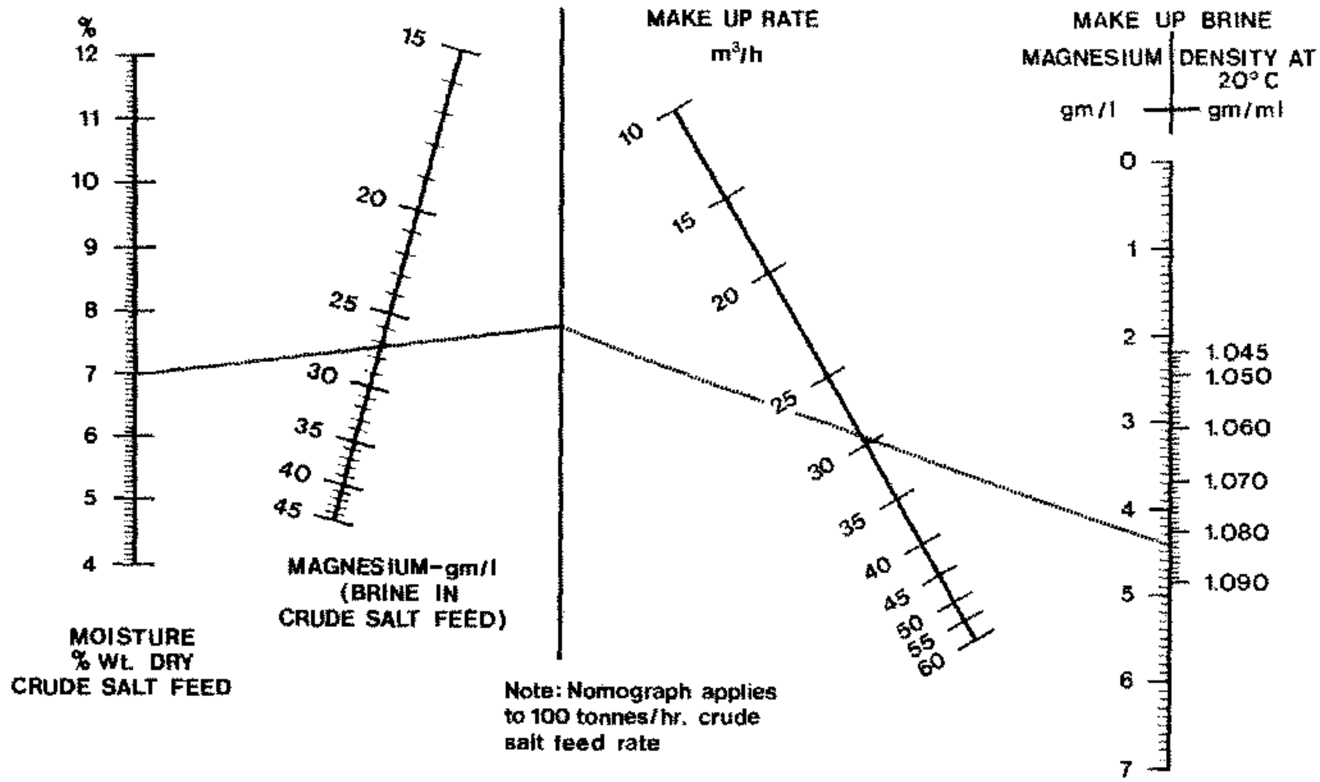


Figure 7. Nomograph.

SUMMARY

Of a number of different methods for salt field design, that used by Bonython proved most suitable in the case of Dampier and provided a basis for process control until such time as sufficiently reliable meteorological information became available. Experience has shown that accurate process control requires close attention to meteorological information in addition to pan evaporation readings.

The selection of series crystallizers for the basic design has proven to be of advantage in reducing processing losses. It also provides an additional source of operating flexibility which, combined with that available in other areas, and the approach to quality control, has made it possible to meet the current market requirements of a consistent and high quality product.

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