Factors in the Design of Solar Salt Plants
Part I. Pond Layout and Construction

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ABSTRACT

The design and construction of solar salt plants has always been an art based upon prior experience and a small amount of technical data. Now, however, as the world demand for salt increases, and a higher yield per acre and greater salt purity becomes more important, the need to employ more basically engineered pond systems arises. By careful attention to both economics and engineering, possible site locations can be extended over those currently considered, and the pond area can be more exactly determined and balanced between the various components within the system. The arrangement of canals and roads can be optimized, as can be the pumping, weir, and brine control equipment. The most effective dikes design can also greatly extend the usable area of a pond system, reduce leakage, and aid in the pond system's operation. Techniques for these and other aspects of solar pond design are discussed in detail.

INTRODUCTION

Solar evaporation salt plants have been known since the earliest writings of man, and their use continues to be a major world-wide industry. They are now, just as they have been for centuries, capable of producing large quantities of fairly pure salt at a comparatively low price. However, with the growing world population demands and the inevitable competiton from other sources, the need for new solar plants, and for increased capacity from the older ones, has necessitated an increasing awareness of the factors relating to their design and most efficient operation.

This series of papers will attempt to examine the technical factors involved in solar plant design, considering: (1) pond layout and construction, (2) the optimum operation of solar ponds, (3) harvesting, washing, and handling of salt, and finally, (4) the production of by-product chemicals from bitterns. The first two of these topics, or the factors involved in solar salt plant location, pond layout, and pond construction will be considered in the following paper.

SITE LOCATION

There are many features to be considered in the location of a new solar salt plant, and any one of them can be controlling. However, if the plant is to be both technically and economically successful, all of the following factors must be at least reasonably favorable.

Marketing and Inexpensive Transportation. With the present keen world-wide competition among salt producers, it is doubtful that any new large salt operation could be successful unless it had a relatively strategic location to its marketing area: either being close to the market, or adjacent to favorable transportation facilities. Many of the other factors determining location can be compromised or designed around, but not sales and this, of course, is basically dependent upon the delivered price of the salt.

Being near large population centers would be the ideal situation, but next best would be a location adjacent to deep water shipping, or on inexpensive barge or rail lines. As an example of this, the two largest West Coast producers have grown and prospered because of their deep water facilities and ability to serve very large marketing areas, while Salt Lake operators, with high inland freight rates, are restricted to a very small marketing (population) area, and thus their size has remained small.

Impermeable, Flat, Pond Areas. Many areas of the world with otherwise adequate or favorable conditions for solar salt plants do not have sufficient areas of comparatively flat impervious soil. Thousands of acres are required for large pond systems, and the leakage must be reasonably low. Ideally, the system can be located on tidal or mud flats, that are low enough to receive some brine by tidal action, and where the soil is a tight clay.

If this condition is not possible there can be many compromises toward it. First, the land need not be adjacent to the brine supply, since with an efficient pumping-conduit system, reasonable distances and elevations can be traversed. Secondly, even though the ponds must be fairly leak free, there are methods of diking or sealing that can fairly inexpensively utilize soil that is apparently porous. These manipulations add to the capital expense of the facility, but may still allow the operation to be economically attractive.

As an additional consideration for a site to be considered for solar ponds, the land's potential dollar income in salt must of course be greater than that of a competitive use. This often may not be the case in areas of high population density or good farming conditions.

Adequate Evaporation Rate. Although apparently the most important factor in the success of a solar pond system, the annual evaporation rate can actually be acceptable over a wide range. Ponds can be successfully operated in areas where there is an annual negative 150 inches of evaporation (East Pakistan), where the annual net evaporation is less than 20 inches (New Zealand), and where the annual net evaporation is over 80 inches per year. The basic requirement is that either the net annual evaporation (difference between the amount of brine evaporated and the rainfall) is substantial enough by itself, or that the net rate in the dry months, or even in some extreme cases, the gross evaporation, is adequate for the economic factors existing at that location.

Considerable meteorological and evaporation data is required to determine the expected evaporation rates. This can be estimated reasonably well by formulas based upon wind velocity, air temperature, and relative humidity (3), but is much better obtained by direct measurement in small test pans. The evaporating pans need to be carefully designed and maintained, but they are basically very simple, inexpensive, and comparatively reliable devices.

Since the evaporation rate varies markedly with brine density, and to a lesser extent pond depth, these variables should also be examined. (See Fig. 5.) A year's record of these rate data, together with meteorological information over the same period and a long-term average, is the most important data needed in the design of a solar pond system. It will define the pond system's size, subdivisions, and production rate per unit area, thus predicting much of the general economics of the operation.

Other Factors. There are many other factors in the choice of a solar salt plant location, but it is rare that any of them would be controlling. A brine supply of adequate strength is sometimes an exception, and of course there is a considerable economic advantage in operating a plant with a 5.0° Be instead of a 2.5° Be brine. However, both can be, and are being used. As with the soil porosity, there are sometimes means of increasing the inlet brine density from its apparent value. Withdrawing the brine from deep waters, pumping from a greater distance to utilize the brine from estuaries or bays where the concentration is higher, receiving desalination plant effluents, etc., may all conceivably be economic possibilities.

The need for an adequate disposal area for the bitterns, and one that will not short-circuit to, and contaminate the inlet brine is also important. Furthermore, the location will be more economical if near an area of adequate labor and supplies, but these factors are seldom critical.

The general conclusion from the above observations on plant location is that the requirements for economical solar salt plants are quite demanding, but by careful analysis they may be considerably less restrictive, and solar salt plants may be located in areas not previously considered practical.

POND LAYOUT

Optimum Size. The area requirements for a given production rate vary directly with the brine feed density, seepage losses, and the applicable evaporation rate. A simplified calculation of this area can be made as follows: Assume (for example) 20"/year net evaporation rate, inlet brine density 3.5° Be, and bitterns discharge at 30° Be. Assume 25% brine leakage in the ponds, occurring linearly throughout the system. Assume a 5% plant washing and handling loss. Total evaporation = 43,600 (sq. ft./acre) × $\frac{20}{12}$ (feet of evaporation) × 62.4 (lbs./cu. ft.)/2,000 (lbs./ton) = 2,265 tons H_2O evap./yr. Entering sea water = 96.52% H_2O and 2.70% NaCl. At 30° Be 97.6% of the water has been evaporated (see Fig. 1), or 96.52 × .976 = 94.3 g H_2O evaporated for 2.70 g × .79 (NaCl yield @ 30° Be) = 2.13 g NaCl.

This equals 43.2 g H_2O evap./g NaCl with no losses, or 43.2/.95 (plant efficiency) × .875 (pond leakage efficiency) = 53.2 g H_2O evap./g NaCl in the actual pond system.

The production rate is thus 2,265/53.2 = 42.6 tons NaCl/acre of pond. This yield would be directly proportional to the effective evaporation rate (i.e., 30"/yr. = 64 tons/acre), and approximately directly proportional to the inlet density (°Be), and inversely proportional to the leakage rate. These factors are thus seen to be very important to the system's productivity. It is also seen that the acreage has to be very large, i.e., 23,500 acres per million tons of salt for the example given.

The cost of pumping brine on the above basis, assuming a 10' lift and .6¢/Kwhr. power would be: $\frac{1,125\ (53.2 + 1.3)\ 2,000 \times 10}{33,000 \times 60 \times .75} \times .746 \times .6 = .38¢/\text{ton NaCl}$.

This number is sufficiently small to allow many times that lift if required to find an adequate pond location, but of course the total pumping costs of a pond system can be a major operating expense. It does point out, however, the flexibility that may be built into a pond's brine handling system without undue additional expense.

The subdivision of the pond areas can also be accomplished by similar calculations to that shown above. For instance, with 3.5° Be inlet brine, and operating in an area of very favorable evaporation, an essentially linear evaporation rate with density may occur over the entire range from sea water to 30° Be bitterns. Knowing that 92% of the water evaporates from normal sea water in progressing to a density of 24.5° Be, the integrated average rate over that period can be found. This value is 86.4"/year in one large solar operation. Also, 5.7% of the original water is evaporated in concentrating from 24.5° Be to 30° Be at an integrated rate of 39.0"/year in the salt crystallizing ponds. The salt ponds' area would then be:

$$92/86.4 = 1.065$$
$$5.7/39 = \frac{.146}{1.211} \quad : \quad \frac{.146}{1.211} \times 100 = 12.1\%$$ of the total, or a ratio of concentrating to

crystallizing ponds of 7.3/1. If the pond leakage were linear in all ponds, the ratio would remain constant, but since an endeavor is usually made to have the crystallizing ponds the tightest in the system, this ratio is usually somewhat distorted in favor of the concentrating ponds.

For an area where the evaporation rate is quite low (as in New Zealand), the average integrated evaporation rate for the concentrating ponds is 21.3"/year (net for the dry months), and 12.8"/year for the salt ponds. This would make the salt ponds 9.3% of the total area, and the ratio of concentrating to crystallizing ponds 9.7/1.

As a point of interest, the production rate for these two areas, assuming the 25% linear leakage rate, would be:

(1) $\frac{80.7}{20} \times 42.6 = 172$ tons per acre in the total pond system

or 172/.121 = 1,430 tons per acre of salt ponds

and, (2) $\frac{20.6}{20} \times 42.6 = 43.9$ tons per acre in the total pond system

or, 43.9/093 = 472 tons per acre of salt ponds.

DEPOSITION OF SALTS DURING THE EVAPORATION OF SEA WATER, 25°C.

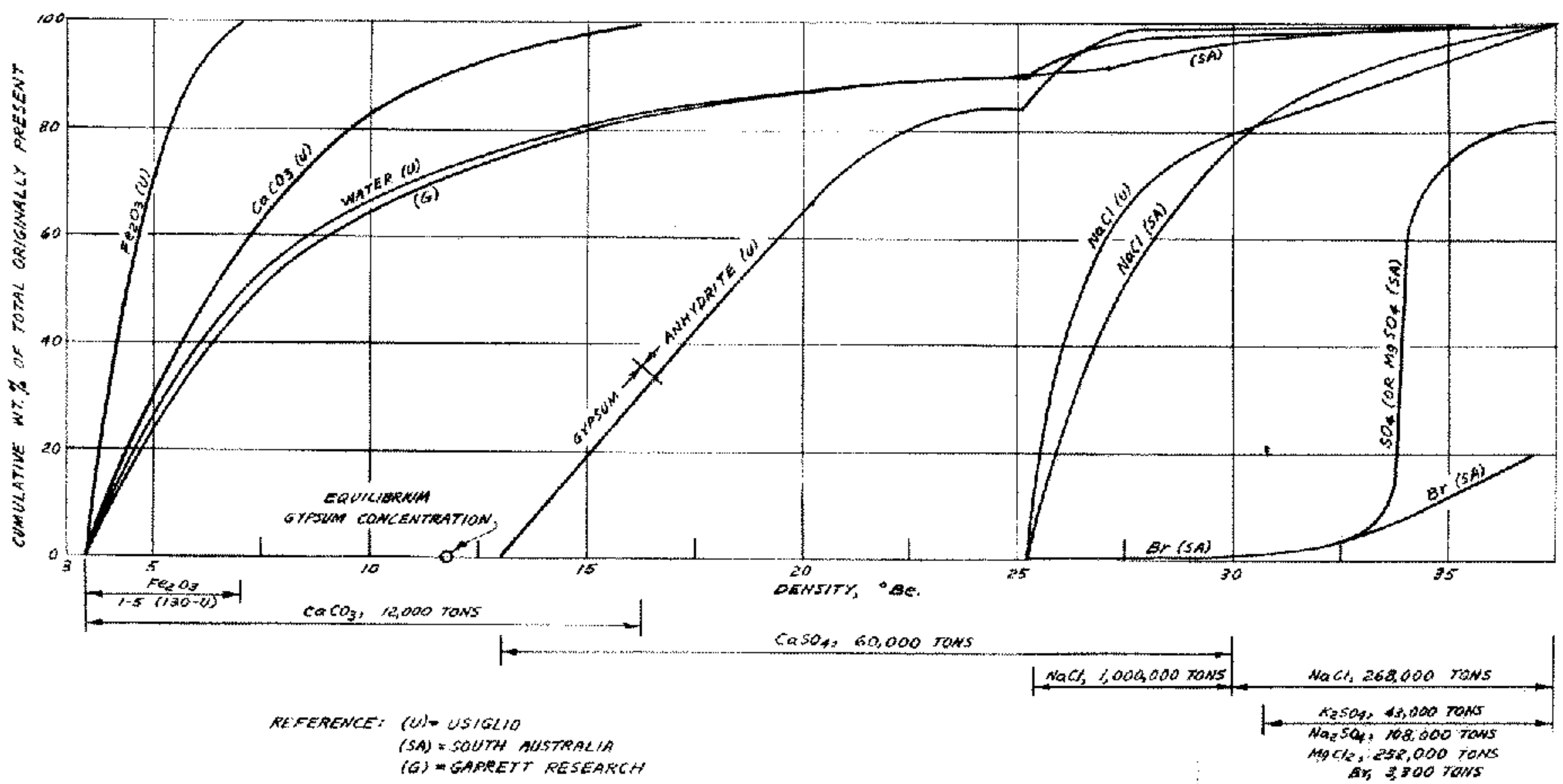

Figure 1

The first case would deposit about 9.4 inches of salt per year (assuming a deposited salt bulk density of 90 lbs./cu.ft.), and the second case, 3.1 inches per year. These two cases probably represent close to the two extremes possible for large commercial operations. Figure 2 summarizes the variation of area required in concentrating to various densities for these examples.

The actual pond subdivisions should be largely based on the elevation contours and geometry occurring in the pond area. In general the concentrating ponds should be as large as is consistent with maintaining the desired pond depth and preventing the formation of dead areas, or short-circuiting. Not all of the concentrating ponds need to be as separate units, since flow path control baffles can be equally effective in providing an orderly brine flow through the system. However, to best control density, some wiers and gates are required, allowing the pond depth to be manipulated.

The general requirements of a controllable brine flow path do not actually set a limit on the concentrating pond size, but in almost all cases the geometry and the contours do limit the size to somewhere between 500 and 1,000 acres. It is usually found that beyond this size the depth along one edge of the pond becomes too great, or that the number or location of pumps or wiers becomes excessive. It is also possible that the risk of wave action damage becomes too great with the larger ponds, but this is often controllable by other means.

The desire to have large ponds is to lower the capital cost of the system, and simplify and reduce the operating costs. However, neither factor is important enough to sacrifice efficiency, so the concentrating ponds can actually be any reasonable size. The salt crystallizers, on the other hand, need to be based upon a much more careful balance of economics of down time for harvesting, draining, and refilling, plus the possible change in salt quality (hardening and becoming contaminated), against the savings to be made in handling and harvesting costs. This will depend upon harvesting machinery and methods employed, and the period in the season when harvesting takes place, but it is a value that is subject to at least an approximate optimization.

Arrangement of Canals, Roads, and Piping. The long-range planning of canals and roads all too often either does not receive adequate attention in the initial layout, or else physical obstacles prevent an efficient design. For the maximum effectiveness, brine feed canals to the salt ponds should be positioned to take advantage of gravity flow if possible, to quickly fill ponds, to allow

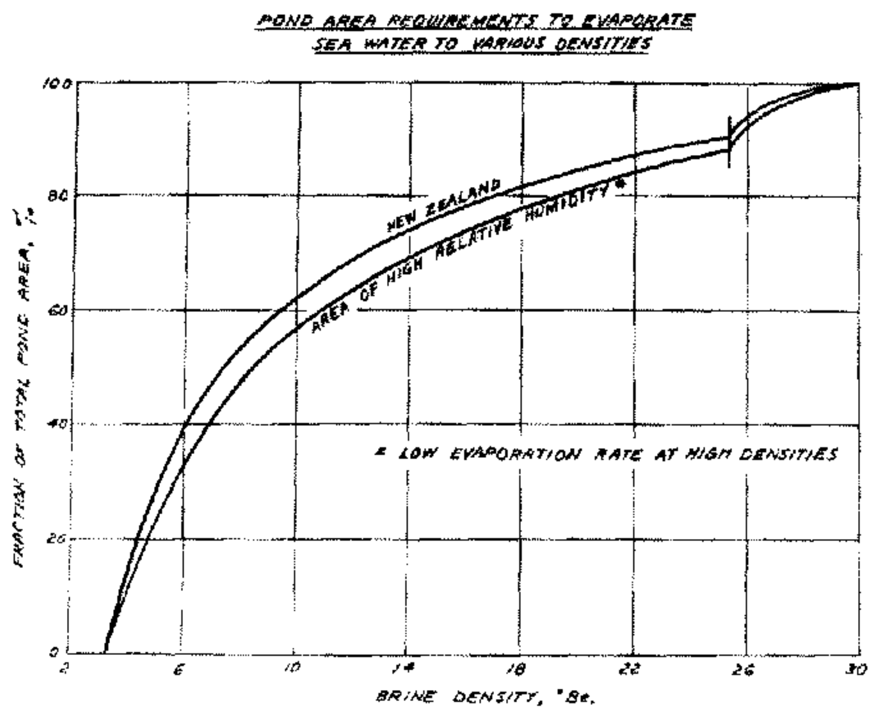

Figure 2

by-passing of ponds being harvested or repaired, and to be easily cleaned. The bitterns canals should be located where the wind action will help in the orderly flow through the pond and their being drained, where draining pumps can be easily set up, and delivering to an area where the bitterns can be adequately disposed of. In general pickle and bitterns canals should be parallel and opposite each other to best take advantage of the contours and wind action. They should also be positioned with respect to roads so that they do not provide obstructions and that the conduits and flumes under the road can be easily cleaned and maintained.

Canals in the concentrating section of the ponds generally have a quite different function and are mainly needed to move the brine from lower to higher elevations. As with the conduits providing fresh brine, or disposing of bitterns, they can possibly be more economically constructed as pipes to take advantage of siphon effects, or to aid road or dike crossings, than as open flumes.

Roads within the pond system are of necessity constructed on dikes, and often are of three types: main product haulage roads, principal access roads, and minor maintenance roads. The former need to be constructed almost of main highway quality, and consequently it is important that the ponds adapt to them to provide the shortest and most favorable haulage distance. Crowning and surfacing these roads can be a problem because of the quantities of bitterns spilled from the trucks during hauling, with both its slippery and deteriorating effect. It is probable that only a mildly crowned asphalt surface provides the best economic balance between first cost and maintenance, but in many situations it may not be practical.

Pond Arrangement. As with other features of the pond layout, the exact arrangement may be dictated by the physical features of the land. However, within the limits that can be manipulated, several factors should be considered. First if there is a prevailing wind direction, or a direction from which most of the storms originate, the ponds should be oriented as much as possible to have the short dimension of the pond in the direction of the wind. The size and violence of waves is directly proportional to the distance they have traveled (1), so this should be minimized. Secondly, the configuration should be such as to provide the most positive flow path with the least number of wiers and pumps, and the first cost of wiers and pumps, as well as their operating cost, should be optimized. Finally, the orientation should route the weakest brines to the most porous or potentially damaged or flooded areas, and the pickle liquor and the salt ponds to the most impervious and closest areas to the processing plant and shipping point. These factors are all fairly obvious, but, nevertheless, the careful attention to the various desirable features in the design can be very profitable. Layouts to obtain the maximum help in brine filling and flow patterns from the wind action, control gates to aid in quick and effective adjustment of densities and flows, minimum energy cost and maintenance, a plan for future expansion, by-passing arrangements, etc., all can contribute significantly to the ease of operation and total economics of the plant.

DIKE DESIGN AND CONSTRUCTION

Soil Survey. In deciding upon a suitable solar pond area, and later in constructing the ponds, one of the most important tools is a comprehensive soil survey. Its main purpose is to determine the porosity of the soil, but more specifically, it must define what porosity exists at different areas of the proposed plant, what discontinuities such as sand lenses, what former river and slough deposits are present, and what the general soil bearing pressure is. The method of obtaining this data is to take core samples in every area of interest (this usually means hundreds of cores) down to a depth well into a good clay zone. The various formations occurring in the cores should be noted, and porosity tests made on many representative zones. The core samples can be taken by rapid and only moderately accurate methods (i.e., precise "undisturbed" samples are not required), but they must be carefully and painstakingly evaluated. When completed, isopach maps or the impervious soil zones should be plotted.

Soil and Dike Sealing Methods. In almost every large area that might be considered for solar ponds there are some zones that are too porous on the surface to be used. However, if the soil survey shows that there is a satisfactorily impervious soil a reasonable distance below the surface, the area still may be used, and sometimes without a great additional expense. In other words, if there is a major clay seam or a series of smaller seams that are continuous over the area desired for the pond, even if they undulate up and down with loam or sand filling the depressions, a tight pond can be constructed by trenching into the clay, and then backfilling the trench with good clay from an adjacent "barrow" ditch. With the large equipment used in constructing a pond system, such a procedure can seal off 10 to 15 feet of sand, if necessary, without trouble. Of course, such a method greatly increases the diking cost for deep trenching, but if only sealing two to five feet of sand, very little extra cost may be involved since the surface soil under a dike almost always needs to be removed anyway (because of sand or organic debris) and only a slightly greater strippling depth is required. (See Fig. 3.)

A clay dike seal such as described above is very effective and they are becoming widely used. It will form a tighter pond in almost all cases, and often is the means of using otherwise completely unacceptable areas. The presence of any underlying clay strata is a fairly common occurrence with many coastal or playa areas, so the method has a fairly general applicability.

The use of artificial membranes or soil sealants is often considered in solar ponds, and they have been widely used in water reservoir construction. However, it can be categorically stated that at the present time there are no known membranes or soil sealants that would give effective results at a price acceptable to sea water salt operations. There are a few solar ponds operating with membrane linings, but they are very special cases evaporating rather concentrated and valuable brines.

The possible use of membranes in dike construction, however, is a different matter, for the comparatively small quantities of membrane required and its ease of application can often make it an economical substitute for a mud lining. Because of its good puncture resistance and strength, butyl rubber is presently the preferred lining for such service, but less expensive chlorinated polyethylene or even high-strength vinyl formulations may provide a satisfactory seal.

Dike Construction. As discussed above, the simplest and cheapest pond construction is merely to scrape off surface debris and sand and then construct a dike from adjacent barrowed mud. Basically, there can be no other economical method for large solar pond operations, but in

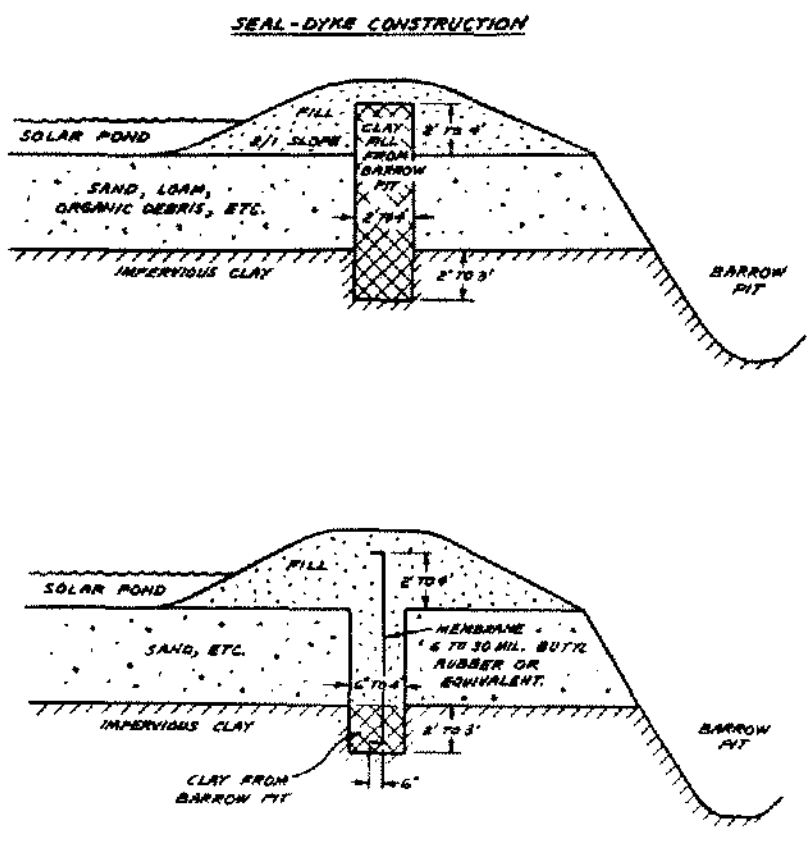

Figure 3

some salt ponds, and smaller concentrating ponds, wooden dikes are used. The usual purpose is to allow harvesting equipment to come closer to the dike wall without picking up mud, but in some cases it also serves (when mud filled) as the sealing wall.

Besides the requirements for the dikes to seal the ponds, and provide road surfaces, the main demands upon them are to resist the wave action that periodically occurs. Minor dikes are usually given two feet of freeboard height (distance out of the water) while main dikes are constructed with four or more feet of freeboard. Normally step slopes (i.e., 2/1) on the sides provide better wave resistance than very shallow slopes, and rip-rapping of some type is necessary to provide a comparatively long maintenance-free life. However, since this is expensive, a program of routine rebuilding will often be used to replace dike soil that has been eroded away. For heavy sea walls, of course, a considerably stronger construction is required than with interior dikes.

SUMMARY

There are many other factors than those considered above that enter into the design and construction of solar salt plants, since only the more important aspects of the design, and those most subject to improvement have been considered. (Many excellent references occur on this subject, as for example, some of the papers presented at Bhavnagar -- 2.) In general, it may be stated, however, that newer dike design methods, and careful attention to the general technical principles involved, can extend the area suitable for solar pond locations, and considerably improve their later output and cost of operation.

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