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MANAGEMENT OF BIOLOGICAL SYSTEMS FOR CONTINUOUSLY-OPERATED SOLAR SALTWORKS

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ABSTRACT

The goal of every solar saltworks with seawater intake--continuous and economic production of high quality salt (sodium chloride) at design capacity—requires ability to simultaneously manage and coordinate physical systems with biological systems in the concentrating and crystallizing ponds. This effort requires close control of specified salinities, depths, and brine transfers, frequent surveillance and adjustments of planktonic and benthic communities and their key microorganisms, and timely recognition and correction of developing problems. This report reviews features and concepts that facilitate biological and physical management, considers causes and effects of common and severe disturbances and their solutions, and provides information that enable biological systems in the ponds of a solar saltworks aid rather than harm salt production.

KEYWORDS: *Aphanothece halophytica*, *Artemia*, biological management, *Dunaliella salina*, marais salants, red halophilic bacteria, salina design, salinas, saltfields, solar saltworks

1. INTRODUCTION

Solar saltworks (marais salants, salterns, saltfields, salinas, solnitzi) use energy from wind and sun to evaporate seawater, inland brines, or subterranean saline water in outdoor ponds and manufacture salt (sodium chloride) or other valuable products. Sodium chloride, the chief or only product of most solar saltworks, is produced mainly in seasonal and continuously operated salinas. The information below pertains only to continuously-operated solar saltworks that manufacture sodium chloride uninterruptedly from seawater during an entire year. Artisanal, seasonal, and inland salinas have been considered elsewhere (Davis, 2000).

Continuously operated solar saltworks maintain flows of water and desired salinity gradients throughout the circuit of ponds, harvest one or more times in a 12-month period, and maintain salt floors in their crystallizers. The salt floor--a 10 to15 cm layer of sodium chloride above which the crop is deposited--is not harvested; it enables crops nearly free of insoluble substances and supports grading, harvest, and hauling vehicles.

The salt manufacturing process begins with evaporation of seawater in a connected series of shallow (40 to 60 cm) concentrating and crystallizing ponds. In the downstream flow, salinities in each successive pond increase until water of near saturation reaches the brine storage pond. After attaining saturation with sodium chloride, brine repeatedly flows into crystallizer ponds (crystallizers) where evaporation continues, salt is deposited on the floors, and the overlying supernatant liquid (bitterns) periodically removed until crops of 5 to 20 cm of salt accumulate. The crops are harvested, washed, and stockpiled for a time to decrease contaminants and water levels, and then marketed. By this process the purity of salt may exceed 99.7% on a dry basis.

Solar saltworks may consist of a single series of directly connected ponds, two or more separate series of ponds, or they may be composed of several parallel series whose brines join at one or more points (e.g., Perthuisot, 1982). The latter arrangements permit maintenance of dikes, ponds, pumps, floors and gates without interrupting production of salt, facilitate control and management under adverse conditions, and enable independent flow rates through the circuits.

This paper is based mainly on the author's experiences and research at continuously operated saltworks, as well as his laboratory experiments and study of the pertinent literature in basic science journals and trade publications. This report reviews physical and biological attributes of saltworks that enable continuous and economic production of high quality salt at design capacity. The paper also includes commonly encountered problems, their causes and successful solutions, and provides concepts, features, and management methods to cope with disturbances, and improve performance of physical and biological systems.

2. SELECTED ATTRIBUTES FOR CONTINUOUS AND ECONOMICAL PRODUCTION OF HIGH QUALITY SALT AT DESIGN CAPACITY

Physical Attributes of the Saltfield

Suitable locations for a saltworks site require climates with low monthly and annual rainfall, nearly continuous, vigorous winds, nearby adequate shipping facilities, soils of pond floors and dikes with an important water-impervious component, and topography that facilitates flow by gravity. Criteria for locating the seawater intake include constant availability, low concentrations of organic and inorganic nutrients, and low content of microorganisms, sand, silt, and soil. Ponds of the low salinity range (S.G. 1.025 to 1.074) occupy about 60 percent of the concentrating area, those of the intermediate range (S.G. 1.074--1.160) 25 percent, and of the high range (S.G. 1.160 – 1.215) 15 percent. The ratio of surface area of the concentrating ponds to crystallizers is 12:1; the latter, fed saturated brine at S.G. 1.215, discharge bitterns at S.G. 1.250.

The downstream flow from seawater intake through the brine storage pond is managed to establish and maintain a desired salinity gradient, and to maintain unchanging salinity at every point in the ponds. This steady state physical system is facilitated with adjustable gates, standby pumps at each pump station, manually obtained or automatic salinity sampling at strategic locations, and close control of brine depths and movements.

Biological Attributes of the Saltfield

Steady state physical systems in appropriately designed salinas coupled with biological management techniques that maintain in each pond only small changes in the kinds, numbers and concentrations of living organisms, allow development and maintenance of communities of organisms able to thrive (grow and reproduce best), power the biological system at desired levels, and continuously contribute essential services for salt production. These highly effective communities and their activities are herein defined as a **desired biological system**.

Most concentrating ponds possess a planktonic community (organisms suspended in the water) and a benthic community (organisms living on pond floors). Each community consists of producer organisms—algae, cyanobacteria, and certain bacteria--that manufacture organic substances from light energy, carbon dioxide, and inorganic nutrients (this is photosynthesis), and power the entire biological system at desired levels, and consumer organisms –*Artemia*, brine flies, bacteria, ciliates, crustaceans, mollusks, nematodes--which use organic substances to power their physical activities, growth and reproduction.

In the flow from low through high salinity, 1) the composition of planktonic communities gradually change from low levels of diverse groups of species (kinds) in low salinity to high concentrations of few important kinds in high salinity, 2) photosynthetic production of new organic substances that exceed consumption gradually changes to consumption surpassing production, and 3) concentrations of dissolved and particulate organic substances increase in the water. As the suspended organisms flow downstream from one pond to the next with higher salinity, they die and release their contents which become nutrients for the new succession.

Benthic communities functioning to control leakage and trap nutrients remain firmly attached to floors, and maintain desired thicknesses and species composition and concentration in each pond. In the downstream flow, the communities change from loosely organized mats of many species (in low salinity) to leathery mats of several layers dominated by fewer species (in intermediate and high salinity). The microorganisms of benthic communities compete for nutrients, aid control of gypsum accumulation (Geisler, 1981) and help prevent dominance of undesirable mucilage producers.

Rewards for saltfields with the above physical and biological attributes are realized in the final stages of salt production. In crystallizers, the salt floors and crops remain firm and white. Assays of typical samples of washed and stockpiled salt ready for market are H_2O = 2.5 – 3.0%, Ca = 0.03%, Mg = 0.02%, and SO_4 = 0.11%. Ten percent to 12% losses in the wash process and a short time on the stockpile bring the salt assay to the above world standards.

Crystal characteristics of typical samples of salt ready for market consist of high percentages of crystals that are solid, clear, single, and at least 1 to 2 cm in their longest dimension, and low percentages of crystals that are hollow hoppers (layered, pyramids), conglomerates (fused hoppers), or small cubes (1 mm or less on a side).

3. KEY ORGANISMS

Aphanothece halophytica, *Dunaliella salina*, *Artemia*, and the Archaea (herein designated the red halophilic bacteria), are key organisms common in most solar saltworks. Their presence or absence, colors and concentrations, and performance under favorable and adverse conditions are highly important to salt production and require special attention and management efforts.

***Aphanothece halophytica*.** *Aphanothece halophytica* are blue-green algae (cyanobacteria), photosynthetic, and exist as single cells or colonies of cells, whose colors range from green to blue-green to yellow. *Aphanothece halophytica*, harmless in desired biological systems, are common in both communities of the concentrating ponds, but grow and reproduce best in intermediate salinities and do not survive in crystallizers. Disturbances often cause *Aphanothece halophytica* to reproduce at high rates, exclude competing species, and release massive quantities of mucilage highly damaging in the ponds of intermediate and high salinity, and crystallizers.

Dunaliella salina. D*unaliella salina*, members of the green algae group, are also photosynthetic but exist only as single cells. Almost exclusively planktonic, *Dunaliella salina* in desired biological systems begin life as green cells in the intermediate salinity range where they grow and reproduce best. After they flow downstream to reach high salinity and crystallizers, *Dunaliella salina* remain alive, gradually change color to bright orange-red, enlarge, become spherical, and accumulate glycerol and beta carotene. Slow and fast developing disturbances often cause *Dunaliella salina* to reproduce massively, and release damaging quantities of organic substances highly detrimental to salt production.

***Artemia*.** *Artemia* (brine shrimp) reproduce and grow best at intermediate salinities where they are able to develop large and self-sustaining populations. By ingesting microorganisms, organic and inorganic particles, the animals are an important bridge between the substances received from upstream ponds and produced at intermediate salinities, and the downstream high salinity ponds and crystallizers. This important activity results from efficient conversion of the organic substances *Artemia* ingest and convert to energy, carbon dioxide and water (Gibor, 1957), and their release of wastes in small, bag-like fecal pellets which fall to the pond floor and become incorporated into the benthic community. Upon reaching high salinity and the crystallizers, most *Artemia* die and are consumed by the resident red halophilic bacteria.

Red Halophilic Bacteria. Red halophilic bacteria occur in every salina, are common, aerobic (require oxygen), and abundant. Although they occur throughout the high salinity range in concentrating ponds, red halophilic bacteria reach their highest concentrations in the crystallizers, where their numbers are often sufficient to color the brine, aid solar energy absorption and evaporation, and consume significant quantities of dissolved and particulate organic substances.

4. ESTABLISHMENT AND MAINTENANCE OF DESIRED BIOLOGICAL SYSTEMS

Establishment of Desired Biological Systems

In most solar saltworks with appropriate design, biological systems develop together with the steady state physical system. To accelerate the steady state system and community development, success has been achieved with judicious application of commercial fertilizers to the ponds (Davis, 1978), rerouting highly saline brines to desired areas (Garrett, 1966), and by continuously filling the entire system of ponds with the shallowest possible layer of seawater; as waters of different salinities appear they are moved to appropriate ponds (de Flers, 1967). After desired biological systems develop, appropriate adjustments to the physical systems balance the quantity of organic substances produced by photosynthesis with the amount of organic substances used by the consumer organisms.

Maintenance of Desired Biological Systems

A minimal maintenance strategy requires routinely gathered data and observations on the physical and biological systems, manual or computer assisted analysis of the evidence (Burnard, 1993), and appropriate display and implementation of the information. This effort not only determines the status of the biological system, but helps to anticipate, identify and correct developing problems before disasters occur. Typical measurements of the physical system include salinity, depths, and flows, condition of dikes, quantity of accumulations on floors, peripheries, and corners of ponds, firmness of the gypsum and salt deposits, widths of mushy salt perimeters, condition of the salt floors, contaminant assay, and crystal characteristics of salt ready for market. Typical biological measurements include composition and concentration of suspended organisms, water color and viscosity, composition and quantification of organisms in each layer of the benthic communities and quantification of organisms above, below and within the gypsum and salt deposits.

5. DISTURBANCES

Slowly Developing Disturbances

Despite less than optimum design and operation, and nutrient-rich seawater intake, many well established solar saltworks achieve economic production of high quality salt at design capacity for a number of years from their outset. However, slowly developing disturbances and their economic consequences commonly occur and are often unheeded until severe effects attract attention.

Causes and consequences of slowly developing disturbances in concentrating ponds include 1) continuous entry of excessive quantities of nutrients at the intake, from land runoff, or from large numbers of visiting birds in the ponds—at quantities greater than required for desired biological systems, 2) frequent severe wave action or excessively fast flows at the intakes of ponds that scour floors and prevent development of benthic communities, 3) too few ponds each with insufficient area that result in large increases in salinity within individual ponds, low diversity of species, insufficient nutrient sequestering and creation of conditions favorable for excessive organic production and release by *Aphanothece halophytica* and *Dunaliella salina*, 4) mixing of brines of different salinities caused by leakage or infiltration across dikes and floors, and back-mixing within ponds resulting in conditions favorable to *Aphanothece halophytica*, 5) use of deep lagoons within the pond circuit (they are without effective benthic communities), 6) decreases of pond surface areas and volumes caused by excessive production of black substances on pond corners and floors, 7) pond surfaces partially to completely covered with filamentous cyanobacteria, hair-like green algae, or floating rafts of mucilaginous *Aphanothece halophytica* that decrease evaporation, result in nutrient-rich and viscous brine that carries dissolved and crystalline gypsum downstream causes ineffective *Artemia* populations, and large *Dunaliella salina* populations in the high salinity and crystallizer ponds, and 9) use of nutrient rich subterranean brines to supplement brines obtained from evaporation of seawater.

Causes and consequences of slowly developing disturbances to crystallizers include 1) ineffective populations of red halophilic bacteria that are unable to control the concentration of organic substances, 2) high concentrations of *Dunaliella salina* that release organic substances (Giordano *et al.*, 1994), 3) mushy perimeters and crops, 4) salt floors unable to support heavy equipment, 5) harvest of layered hoppers, hollow conglomerate and small crystals that retain calcium, sulfate, magnesium, and water, 6) increasing costs in the harvest and wash processes, and the necessity for prolonged stockpile residence or centrifugation to improve the quality of salt.

Cures to combat slowly developing disturbances in concentrating ponds involve techniques to decrease nutrients by 1) allowing intake water to flow through a nutrient-sequestering, shallow pond with wetland plants (DuToit and Campbell, 2002), 2) use of shallow depths in ponds to aid development of nutrient sequestering mats, 3) installation of bird-scaring devices (Davis and Giordano, 1996), 4) mechanical removal of floating and attached algae, sediments on floors and corners, and gypsum deposits, 5) construction and use of additional ponds to increase floor area available for nutrient-removing benthic communities, and to permit narrower salinity ranges in ponds, 6) installation of strategically placed baffles, dikes or other devices to moderate wave fetch, and prevent floor scouring. Cures for crystallizers include removal of soft and mushy perimeters at each harvest, removal and repair of salt floor areas damaged by spills of petroleum products, and periodic replacement of salt floors with accumulated organic substances.

Fast-Developing Disturbances

Events involved in fast developing disturbances include cyclones, hurricanes, and high velocity winds that destroy dikes, permit entry of fresh water or seawater, petroleum spills, and damage to pumps, dikes and gates. Consequences often occurring within days to weeks after the causal events include fast increases of organic substances in the water, viscous brine, change from large numbers of important species to near monocultures dominated by *Aphanothece halophytica* and *Dunaliella salina*, destruction of the salinity gradient and benthic communities, and death of the *Artemia* and red halophilic bacteria populations.

Effective cures for fast-appearing disturbances in concentrating ponds include repair of any physical and equipment damage, reestablishment of the salinity gradient, armoring vulnerable areas of dikes with rip-rap, purging ponds of organic substances (Sammy, 1983), selection of pond depths to favor development of benthic communities, and continuous and massive reintroduction of *Artemia* until functioning populations develop (Magaña *et al.*, 2005). In crystallizers, effective cures include removal and replacement of brine, crops, and salt floors contaminated by mucilage, other organic substances, or petroleum products.

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