BRINE DISPOSAL FROM LAND BASED MEMBRANE DESALINATION PLANTS: A CRITICAL ASSESSMENT

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INTRODUCTION

The earliest applications of desalination technology date back to the use of boiler condensate on early "steam-ships". Installation of large-scale land-based desalination facilities began in the Middle East shortly after the end of WW II. These saline water evaporators were sited along the Persian Gulf and other costal locations. An especially large increase in desalination capacity began in the late 1960's as a result of the proven reliability of reverse osmosis membrane desalination systems. In general, brine disposal at costal sites has met with few problems provided that careful consideration was given to sitting the outfall conduit.

Following more than three decades of continuing expansion of sea water desalination capacity at costal sites, considerable interest has now shifted to reclamation and reuse of inland water sources. Worldwide desalination capacity has more than doubled in the past two years according to a recent article by Wangnick [1] and this trend is expected to continue in the near future. Of special concern is the ongoing increase in salinity of natural water resources in the South Western United States and especially in Southern California, which depends, to a large extent, on the Colorado River and other water resources, with salinity levels in excess of the U. S. Public Health Service standard [2]. As a result of shortage of good quality ground water and surface water, several states including Florida, Texas, New Mexico, Utah and California, have conducted field studies and/or implemented membrane desalination technology to various degrees.

In the United States, it has now become economically feasible to renovate various natural water sources by membrane desalination processes. Recent development of high performance low pressure reverse osmosis membranes has resulted in a significant reduction of energy costs. At this time, brackish waters in the salinity range of 2,000 – 5,000 mg/L can be brought up to drinking water quality at a cost of approximately \$0.75 - \$1.00 per 1,000 gallons compared with sea water desalination costs in the range of \$3.00 - \$5.00 per 1,000 gallons [3]. In addition, desalination at the salinity range of most surface and ground waters under consideration can be performed at relatively low trans-membrane pressures, in the range of 200 – 300 psi.

Inland desalination plant sitting, presents greater challenges to the designer than building a similar facility at a costal location. The issue of greatest concern involves development of cost effective brine disposal systems, which conform to regional and federal environmental constraints. Such systems often involve acquisition of land and pipeline construction for delivery of waste streams from a large desalination facility. Even at high product water recovery and establishment of brine minimization technology, volumes of highly concentrated plant discharge streams can be very large.

Requirements for brine minimization are clearly illustrated in specifications for a 300 million gallons per day (MGD) membrane desalination plant proposed by the Metropolitan Water District of Southern California (MWD). This plant, designed for 85% recovery, would produce a brine discharge stream of 45 MGD [4].

Systems for brine minimization, presently under study, however, could significantly reduce the plant discharge volume. Operating according to design specifications, such a system would increase product water recovery to 98.5%, thereby reducing the brine stream to about 4.5 MGD. The overall salt concentration ratio ($CF=C_c/C_f$, where C_c and C_f are retentate and feed concentrations, respectively) can be calculated at each stage of the desalination process using the following relationship:

$$CF = \left(\frac{1}{1-R_w}\right)\left[1-R_w(1-R_s)\right] \tag{1}$$

where R_s is the fractional salt rejection ($R_s=1-C_p/C_f$) and R_w is the fractional product water recovery ($R_w=Q_p/Q_f$, where Q_p and Q_f are the permeate and feed flow rates, respectively). As an example, assuming a 700 mg/L TDS level for Colorado River (CR) water, the brine TDS, following a first desalination stage at 99% rejection and 85% recovery, would rise to 4,627 mg/L. Following treatment of the brine stream to achieve a total recovery of say 98.5% (at the same rejection level), TDS levels would again increase to 45,850 mg/L. This calculated value may exceed the solubility of some inorganic salts which are likely to precipitate. It is expected that such a discharge would contain a suspension of various crystalline substances, especially if an enhanced precipitation process is used in the brine minimization system. As a result, handling such a concentrated brine stream would indeed present several challenges.

The major strategies for brine disposal at inland sites are limited to three general categories; 1) Deep Well Injection 2) Evaporation Ponds and 3) Solar Ponds. Several other systems for utilization of waste brine have been proposed, which include, among others, irrigation of salt tolerant plants (halophytic crops) and brine shrimp harvesting [5]. Such approaches have been limited and are certainly not applicable to very large volumes of wastewater. Recovery of inorganic salts with potential commercial value has also been suggested [6], but construction of chemical separation facilities would indeed result in a costly venture. It is important to recognize the prime mission of any desalination facility, which is to upgrade water quality - not to market by-products. To date, proposed by-product recovery systems have not demonstrated economical viability and it seems likely that the cost of by-product recovery would far exceed the cost of the principal product – water.

A system known as zero discharge [7] has also been used in certain situations where waste brine streams are relatively small and available land is limited. This technology has generally been applied to wastewater disposal from power plants, oil refineries and certain mining operations. The final stage of such a system involves thermal evaporation, subsequently providing a solid residue. Energy requirements are large and overall economics unfavorable for handling large brine volumes.

A discussion of the wide variety of the above alternative schemes for brine management is not relevant for the large desalination facility, proposed by MWD. As a result, this report will focus on a review of technological features presented in current literature on each of the three major categories for handling the anticipated large volumes of waste brine from a 300 MGD desalination facility. An "in depth" summary of brine disposal methods by Mickley [8], presents detailed documentation of the impact of regulatory and environmental considerations on the development of this technology. Mathematical models for estimation of concentrate disposal costs are also included in this comprehensive work. An overall review of the current "state of the art" in brine disposal has been presented at a recent “workshop” sponsored by the American Membrane Technology Association [9].

DEEPWELL INJECTION

Deep well injection is presently applied worldwide for disposal of industrial, municipal and liquid hazardous wastes [10]. In recent years this technology has been given serious consideration as an option for brine disposal from land based desalination plants. Deep well injection has been applied successfully for brine disposal from several membrane plants in Florida. Design criteria for these installations, is discussed in a recent paper by Skehan and Kwiatkowski [11]. Injection wells may vary in depth from a few hundred feet to several thousand feet depending on geological considerations at the selected site. Several factors contribute to the overall performance and reliability of an injection well. In general, however, this method of brine disposal is considered the most cost effective as compared with other systems in practice for land based desalination plants [11].

A successful application involving brine generated from salt caverns used for natural gas storage in North Germany was recently reported by Borgmeier [12]. Brine has been continuously injected since 1997 at several carefully evaluated sites to depths ranging between 1,300 and 2,000 meters. Cumulative data for this injection period is carefully documented in this study. Prior to drilling any injection well, a careful assessment of geological conditions must be conducted in order to determine the depth and location of suitable porous aquifer reservoirs. This paper was concerned primarily with the geophysical aspects of deep well injection. No information on brine chemistry was presented, however, “brine conditioning” and filtration were considered necessary prior to injection.

The nature of subterranean strata must be carefully considered in selecting a suitable well location as stated by Rhee et al [13]. Most stratifications consist of sand (porous medium) and shale (confining layers). Mathematical models developed in this paper, were used to determine the permeability and solution confinement capability of strata with different ratios of sand to shale. This study, primarily applicable to hazardous waste disposal, can also be used as a model for deep well injection of any concentrate where inadequate waste solution transport and confinement could result in contamination of surface and groundwater resources.

The paper by Saripalli, Sharma and Bryant [10] presents an excellent survey of current literature on deep well injection of various aqueous waste streams in the United States. Research efforts, by these investigators, were focused on physical factors influencing well performance. A measure of the effects of plugging and damage to subterranean formations on injection well performance was expressed by injectivity (I), defined as the ratio of injection rate (q) to the difference between well flowing pressure (P_{wf}) and the average formation pressure (P_r) given by the following equation.

$$I = \frac{q}{P_{wf} - P_r} \tag{2}$$

Injectivity is impacted by several factors, which include the chemical and physical quality of the injected fluid, injection rate and pressure, as well as the nature and physical properties of subterranean strata. One of the most important constraints on stable injectivity is the presence of suspended solids in the injection fluid. Frequent measurements of total suspended solids (TSS) are required to insure steady well performance. A mathematical model developed by Saripalli et al. [10] has been used successfully to simulate injection well performance. Outcomes of this model indicate that high TSS in process fluids, low injection rate, low injection pressure, and low porosity and permeability of the well strata all contribute to rapid well plugging and diminished injectivity.

At this time, more than 800 wells are in operation in various parts of the United States for disposal of aqueous solutions of toxic and hazardous wastes [10]. Disposal of brine from desalination facilities is not presently in practice in this country with the exception of Florida [11], where several wells processing membrane plant discharge have been operated successfully. Deep well injection for brine disposal in California has not, as yet, been considered, since large land based desalination facilities are presently only in the planning stage. A possible solution for deep well injection in Southern California could involve utilization of oil wells, which are no longer in use [14]. If this option is technologically feasible, desalination plant siting, would need to be carefully planned.

According to Mickley [8], deep well injection is a reasonable method for brine disposal provided that long-term operation can be maintained, in order to dispose of large volumes of process fluid. Drawbacks of this technology are: (1) selection of a suitable well site; (2) costs involved in conditioning the waste brine 3) Possibility of corrosion and subsequent leakage in the well casing; (4) seismic activity which could cause damage to the well and subsequently result in ground water contamination; and (5) Uncertainty of the well half-life which can only be estimated using mathematical simulation techniques as described in reference[10]. Models for estimation of capital and operating costs, for conditions of stable well performance, have been developed by Mickely [8].

EVAPORATION PONDS

Evaporation pond technology is practiced primarily in the Middle East and to a lesser extent in arid regions of Australia. At this time, it is probably the most widespread method of brine disposal from inland-based desalination facilities. This disposal system is especially effective in regions with low rainfall, and where climatic conditions are favorable for steady, and relatively rapid evaporation rates. In addition, desalination plants are often sited at locations where the cost of adjacent level land is relatively low.

An excellent assessment of this technology and review of current literature is presented by Ahmed et al [15]. This effort, sponsored by The Middle East Desalination Research Center, presents detailed information concerning the design and maintenance of evaporation ponds. The authors also provide a discussion of brine chemistry as impacted by process water quality as well as chemical additives for pretreatment and membrane cleaning strategies. According to the above study, the pond open surface area (A) and minimum pond depth (d) can be estimated from

$$A = \frac{Vf_1}{E_{ave}} \tag{3}$$

$$d = E_{ave} f_2 \tag{4}$$

where V is volume of reject water, E_{ave} is evaporation rate, f_1 is an empirical safety factor to allow for lower than average evaporation rate and f_2 is an empirical factor that accounts for the length of the winter season. The designer of evaporation ponds must carefully consider the surface area, depth and freeboard of such installations, since these factors are determined by rates of concentrate discharge relative to surface evaporation rates. It is noted that freeboard is especially difficult to estimate since it depends on average rainfall and wind velocity in the pond area. It is clear from the above relationship that the area needed is directly proportional to volume of reject water and inversely proportional to the evaporation rate. Although other empirical factors and relations have been suggested for calculating the impact of brine salinity on surface evaporation rates, in the judgment of the authors of this report, evaporation pond design optimization could be best developed experimentally by circulating typical model brine solutions through small evaporation ponds.

The principal environmental concern associated with evaporation pond disposal is pond leakage, which may result in subsequent aquifer contamination. All current installations are lined with polyethylene or various other polymeric sheets. Liner installation must be carried out with care since sealing of joints is critical in order to prevent leakage. Double lining is strongly recommended with leakage sensing probes installed between layers of pond lining.

A survey of evaporation ponds in Oman and the United Arab Emirates has been documented by Ahmed et al [16]. These ponds were designed to process concentrate from several brackish water membrane plants varying in size between 0.35 and 4.0 MGD. Considerable data are presented on the chemical composition of brine in existing evaporation ponds. This work emphasizes the need for careful environmental monitoring of potential pond leakage, since a variety of toxic chemicals generated in plant operation (including chemicals used in membrane cleaning and pretreatment) may pose a potential risk for contamination of ground water aquifers.

A system for enhancement of evaporation pond performance has recently been developed at Ben Gurion University in Israel [17]. This new technology described as the WAIV process involves periodic circulation of pond brine over “wetable surfaces,” designed to increase the effective evaporative surface area. This results in enhanced evaporation, which, of course, also depends on wind speed and direction in addition to relative humidity. It has been estimated in this study that evaporation rates can be increased by 50% in a typical Middle East dry climate. If proven effective in practice, evaporation pond size could be significantly reduced.

Existing literature indicates that application of evaporation ponds is a relatively simple and straightforward method of brine disposal. This technology, however, is limited to relatively small desalination plants (less than 5MGD) and generally restricted to arid climatic conditions. Capital costs arise primarily from acquisition of land. It seems evident that evaporation ponds, even with enhanced evaporation technology, could not satisfy the brine disposal requirements of the three hundred MGD membrane desalination plant presently under consideration by the Metropolitan Water District of Southern California.

SOLAR PONDS

Development of salt gradient solar ponds as a renewable energy source began in Israel more than thirty years ago [18]. Although limited in scope, successful power generation by this technology has been demonstrated primarily in arid and semi-arid parts of the world. Recent technical papers have also appeared, describing experimental studies in Italy and Switzerland, in which solar ponds are coupled with thermal desalination systems [19,20,21]. In these experimental studies, the pond is used as a heat source for small multistage flash evaporator units. Use of the pond for disposal of resulting brine was not considered in these publications. Ongoing solar pond studies at the University of Texas [22] involve power generation and thermal desalination coupled with brine disposal for recharge of the bottom (hot) layer of the pond.

Perhaps one of the most innovative system for utilization of solar ponds is described by Engdahl 23] and Hayes [18]. An experimental study, conducted by the California Department of Water Resources at Los Banos, CA. in the early 1980's, developed an integrated system for membrane desalination coupled with brine disposal. A salt gradient solar pond provided hot water cycled through a dual media heat exchanger, driving a turbine for electric power generation. The power was then utilized for electrically driven pumps to provide necessary pressure for reverse osmosis desalination of agricultural drainage water. The resulting RO concentrate was then injected into the hot bottom layer of the solar pond. The overall objective of this system was to provide for brine disposal, heat recovery, and salinity augmentation of the solar pond. Unfortunately, the Los Banos desalting operation was shut down in 1986 as a result of an EPA order for termination of agricultural drainage, which provided feed water for this experimental facility.

Following a careful literature search, the only other references to brine disposal in solar ponds was presented in the Los Banos study and also discussed in a publication by Ahmed et al [23]. In this conceptual paper, the authors consider solar ponds for brine disposal but note the fact that such a method would be limited to small desalination systems. The following quote from this paper appears to highlight the state of the art of land based brine disposal technology at this time.

"Brine disposal is normally seen as a major issue in the engineering design of any desalination facility – yet consideration of brine disposal or its utilization, often appears to be an afterthought in many desalination texts."

CONCLUSIONS AND RECOMMENDATIONS

Development of a viable brine disposal system for the proposed Metropolitan Water District membrane desalination plant presents an unusual challenge. This unique facility, under consideration, would undoubtedly be the largest land-based desalination plant to date. Anticipated discharge volumes of concentrate are also unprecedented. Evaporative disposal would involve acquisition of large tracts of level land at relatively high cost. If injection well technology is selected, it is likely that multiple wells would be required to accommodate brine volumes of at least 4.5 MGD. Handling this highly concentrated slurry would require the expenditure of large capital costs in addition to operating expenses at each disposal facility.

In light of these ongoing economic constraints, it appears that ocean disposal would be the most reasonable alternative. A pipeline over level terrain with a carefully engineered outfall structure would indeed require a very large capital expenditure. However, operational and maintenance costs would be considerably lower compared with deep well injection or evaporation pond technology.

Another possible alternative for salinity management of Colorado River Water would be to build a plant at a costal site. The issue of brine disposal would then be simplified and pipeline construction for Colorado River water would present fewer problems than handling the concentrated slurry, which would result from siting this plant at La Verne. Product water would then be blended with ambient Colorado River water or other sources of lower quality water. The construction of several membrane desalination plants at costal sites should also be given serious consideration.

Diminishing supplies of good quality water in Southern California has again focused attention on sea water desalination. This alternative should be seriously considered for water supply augmentation since recent improvements in membrane desalination technology have significantly reduced operating costs. It should also be noted that various large Middle East locations have successfully combined desalination systems with electric power generation [24]. The merger of these technologies has resulted in a significant economic advantage.

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