# ENVIRONMENTAL IMPACT AND COST ANALYSIS OF DESALINATION SYSTEMS

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## Abstract:

This study aims at studying the environmental effects of desalination byproducts and the cost analysis of desalination systems. Focus was made on the two widespread techniques of seawater desalination; the Multistage Flash (MSF) System and Reverse Osmosis (RO) system. These two technologies of thermal and membrane desalination have a substantial history and their industry is well established. MSF systems induce thermal pollution to its surrounding environment compared with the RO System. The temperature of the RO byproducts are at ambient compared with those of MSF that are typically (5-10) °C above ambient. Salinity of MSF concentrates are 15% higher than the influent raw seawater compared with that of the RO that reaches 100% higher in salinity. This study gives a detailed analysis of the environmental impact of each system, the effect of the byproducts on marine life and appropriate technology selection procedure. The economic analysis conducted was focused on land requirements, capital costs, operation and maintenance costs and depreciation costs. It was found that RO has lower capital and production cost than MSF. If membrane replacement rate is higher or energy cost is lower MSF then shows a slight economical advantage over RO especially in large capacity plants. MSF plants require land areas double that required for RO plants and more construction time for similar capacity plants.

**Keywords**

Seawater, Desalination, Multistage Flash Distillation, Reverse Osmosis, Concentrates.

## 1. Introduction

The basis of all desalination processes is the conversion of part of the influent saline feed water to potable water. This has the inevitable result of a stream of water relatively concentrated in dissolved salts discharging from the plant. The other main characteristic of desalination processes is that they require an input of thermal or mechanical energy in order to achieve separation of fresh water from the saline feed water.

The main consequences of such an input of energy are an increase in the temperature of the brine discharged, rejection of heat and atmospheric emissions associated with power generation. These consequences represent an important feature and impact on the surrounding environment due to the variable significant characteristic of both the aqueous and atmospheric emissions, (Karajeh 2000) and (Mona 1999).

Distillation plants generally require a larger seawater inlet flow than membrane processes, resulting in a smaller rise in salinity of the discharged brine. By contrast, the energy consumption of membrane plants is usually less than distillation although the brine temperature rise is correspondingly lower, (Rami 1999) and (Buros 1990).

Pretreatment with various chemicals are used in desalination to control formation of mineral scales and biological growth that would otherwise interfere with the process. These chemicals, or their reaction products, are in turn discharged with the rejected brine. Certain atmospheric discharges also take place from de-aeration and de-gassing of feed or product water, (Oldfield 1996) and (Morton *et al.,* 1996).

This paper examines and compares the environmental impacts of the two main seawater desalination processes: multistage flash distillation (MSF) and reverse osmosis (RO). The atmospheric emissions and thermal discharges from power generating and/or boiler plants to produce the energy needed for desalination are also evaluated. The economic cost analysis of both systems is also demonstrated.

## 2. Process description

RO process consists of three main steps: (a) pretreatment, (b) membrane passage and (c) post treatment, (Ibrahim and Abdulrahman 1995). In the post-treatment step, product water passes through a decarbonation system, a pH adjustment system and a chlorine dosing system to comply product water with the required bacteriological standards.

The purpose of the pretreatment step is to avoid any risk of clogging, fouling or scaling the membrane. Pretreatment is an important aspect of RO systems. All RO systems require pretreatment to remove the suspended solids, sealants, foulants and colloidal matters. Description of RO pretreatment processes are discussed elsewhere, (Al-Mutaz 1994) and (El-Rehaili 1991).

RO plants are formed by combining large numbers of membrane modules arranged in parallel or in series. Possible arrangements of RO modules are: (a) single modules, (b) parallel brine staging, (c) series brine staging (straight or tapered) and (d) series product staging, (Ibrahim and Abdulrahman, 1995).

MSF process has three distinct sections: heat rejection section, heat recovery section and brine heater. The feed water passes through the heat rejection and heat recovery sections. On leaving the first (warmest) rejection stage the feed stream is split into two parts, reject seawater which passes back to the sea and a make up stream which is combined with the recycle stream. The combined stream then passes through a series of heat exchangers and its temperature rises as it proceeds towards the heat input section of the plant; the brine temperature is raised as it passes through the brine heater to the maximum value approximately equal to the saturation temperature at the system pressure. Further detailed description of the MSF system is discussed elsewhere, (Al-Mutaz 1994).

## 3. Environmental impact

### 3-1 Brine characteristics

Desalting seawater to provide potable water fulfills a basic social need and, in general it does this with less environmental impact than other water purification options, (Abufaed et al., 2002). There are no fatal flaws in the desalination technologies under study (RO & MSF) and there is a substantial history of the environmentally safe operation of these desalination plants. However, there is a need to identify, document and understand the environmental concerns that are increasingly being raised with regards to these systems.

The principal environmental impact most commonly associated with the operation of seawater desalination plants is the discharge of warm concentrated brine. Elevated temperature and high salinity has a harmful effect on the surrounding marine habitat. MSF plants typically require an inlet seawater flow around 8 to 10 times the fresh water production compared with a ratio of 3:1 for RO plants.

Thus MSF plants have a significant ecological impact compared with RO plants. The temperatures of RO concentrates are ambient compared with MSF plants that are (5-10) °C above ambient temperature. Thus coupled with the increased dischargers and elevated temperature, the MSF plants provide more risks to the marine and aquatic life. Elevated temperatures reduce the overall concentration of dissolved oxygen in the receiving waters which restrict the life forms to those able to exist at low oxygen levels. Furthermore, extreme temperatures may result in death, whilst sub-lethal temperatures can modify the rate at which biological processes occur thus influencing movement, the onset of maturity, life stage development, growth and size. Excessive temperatures may also lead to changes in individual abundance and population diversity.

RO requires more intensive pretreatment compared with MSF. This is in the form of chemical additives that control scaling, fouling ….etc. The level of these chemicals is generally relatively low and does not normally exceed 10 mg/lit, (Al-Mutaz, 1994). Yet despite this relatively low concentration, some chemicals have a direct or indirect impact on the aquatic marine life. Again MSF brine concentrates although large in volume and high in temperature, are rarely more than 15% higher in salinity than the influent raw water. On the other hand, RO brine concentrates are 100 % higher in salinity than the receiving water.

Another type of pollution resulting from these desalination systems is the atmospheric emissions. These emissions are of secondary importance compared with those stated earlier and can be a result of direct processes like degassing and desertion of feed product water or can be emissions from the associated co-located power plants.

In summary, it can be concluded that desalination concentrates depends on the particular processes involved with many several important shared characteristics. Desalination concentrates may be described as having low levels of process-added chemicals so that raw water characteristics determine final concentrate characteristics. The concentrates are characterized by few parameters other than high total dissolved solids (TDS) relative to the raw water. Finally, it is important to realize that desalination processes do not produce more polluted materials or mass; they redistribute (concentrate) that which is present in the raw water.

**3-2 Brine disposal alternatives**

The environmental concerns associated with the disposal of brine concentrates center on the contamination of surface and ground waters, soil and air by the individual chemical components, temperature and high salinity level of the concentrate. There are several means of disposal of concentrates that are practiced worldwide, (Sanks 1978) and (Motin 1994), these include:

**3.2-1- Surface water discharge**

Surface water discharge is the disposal method used for nearly all seawater plants. The environmental effects from surface water discharge are more readily apparent than those from other disposal options. When used as a disposal means, the following points must be addressed:

i- A mixing system must be designed to provide quick mixing (diffusion) of the brine with the receiving body.
ii- The dissolved oxygen level of the brine must be almost equal to the oxygen concentration on the receiving body.
iii- The pH of both waters must be similar.
iv- The brine discharged must meet the toxicity limits of the sea water standards and regulations.

### 3.2-2-Disposal to sewage treatment plants

The use of this method of disposal has been found to be cost effective for a number of desalting installations. However, practical concerns have been raised on the effect of TDS and heavy metals on the process bacteria, as well as the effect of the added load on the treatment plant capacity.

This method of disposal is suitable when the brine quantities are relatively small in comparison with the total throughput of the wastewater treatment plant. Toxicity and pH levels must also be in accordance with the sewage disposal standards.

### 3.2-3- Deep well disposal

Disposal by deep well injection is the possibility of disposing the brine to a non-potable water aquifer that is structurally isolated from any overlying drinking water aquifers. Monitoring of disposal well integrity and of the water quality of nearby monitoring wells is required in this method. However, this disposal option is not possible in most locations, and where possible, it can be costly.

### 3.2-4- Land applications

Land application of concentrates includes spray irrigation and percolation ponds. Allowable salinity and specific chemical levels are dictated by both vegetation tolerance and salinity of underlying aquifers. Water quality limitations frequently dictate blending of the concentrate with lower salinity water prior to disposal. This disposal method is limited by climate and the availability of land. Continuous monitoring of soil, groundwater conditions and plants is strongly recommended.

### 3.2-5- Evaporation ponds

Evaporation ponds are most appropriate for relatively warm, dry climates with high evaporation rates, level terrain and low land costs. Continuous monitoring of the pond integrity and its effect on the surrounding environment is typically required.

### 3.2-6- Brine concentrators (Zero discharge)

The use of this method although technically feasible, has not been proven for the discharge of brine from desalting facilities. In this method, the concentrate is further treated to reach a dry solid state. In this case the environmental concern is with the disposal of the solid waste and specifically the landfill site and eventually into nearby surface and underground waters.

## 4. Cost analysis

Typical design basis for cost evaluation have been assumed as shown in table 1 for both RO and MSF seawater desalination plants together with the associated power plants. Leitner (1989) listed the capital costs for some RO and MSF plants in various places. Fosselard and Wangnick (1989), performed a comprehensive study on capital and operational costs for different types of seawater desalting plants in the range of (200 to 3000) $m^3/d$. The RO installed equipment cost which includes an energy recovery pump is given by, (Fosselard and Wangnick 1989):

$$C_{RO} = 2400000 * (F/1500)^{0.8} \ \$$$

The depreciable investment costs for MSF is:

$$C_{MSF} = 4650000 * (F/2500)^{0.7} \ (GOR/7)^{0.45} \ \$$$

where:

F= actual output ($m^3/d$).
GOR = gain output ratio or performance ratio
(Kg distillate / kg steam) ranging from 6 to 10.

Van Dijk *et al.,* (1984), presented a formula for RO equipment cost as a function of recovery, R. This formula is given as

$$C_{RO} = 290 \ R^{-0.9} \ (\$ /m^3/ d).$$

**Table 1 Technical design parameters (Leitnes, 1989)**

| Item | MSF | RO |
|---|---|---|
| **Desalination Plant** | | |
| Total dissolved solids (TDS) mg / lit | 35000 | 35000 |
| Maximum brine temperature (°C ) | 96 | - |
| Performance ratio | 10 | - |
| Electrical power ( KWh/ $m^3$ ) | 4.5 | 8.7 |
| Steam temperature (°C ) | 132 | - |
| Conversion factor (%) | - | 35 |
| Membrane life ( Years ) | - | 5 |
| Desalination plant output ($m^3$ / d) | Variable | Variable |
| **Power plant** | | |
| Thermal energy input (MW) | (100-300) | (100-300) |
| Steam to turbine (kg/ sec ) | (60-100) | (60-100) |
| Steam to condenser (kg/ sec) | (20-60) | (60-100) |
| Power to turbo generator (MW) | (50-80) | (70-100) |
| Net electricity output (MW) | (50-80) | (70-100) |

Annual amortization is calculated from the plant lifetime and discount rate as inverse of the present worth equation, (Ericsson and Hillmans 1985):

$$\text{Amortization} = \frac{\text{Capital cost* r}}{1+ (1+r)^{-n}}$$

where:

N = plant lifetime (years)
R = discount rate

The desalination and power plants capital and operating costs are based on the following operating conditions (2003):

| | |
|---|---|
| Power plant load factor | 170% |
| Desalination unit load factor | 85% |
| Plant life time | 20 years |
| Depreciation rate | 10% |
| RO membrane life | 5 years |
| Fuel cost | 25 $/ barrel |

The common items include, civil works (buildings ... etc), seawater intake, outfall electrical switch gear, instruments and control systems. The running costs include fuel, spare parts, chemicals, operation, and maintenance costs.

From previous work and from what was obtained in this study (Table 2), RO units appeared to have lower capital and production costs compared with MSF units for capacities ranging from 3000 to 95000 $m^3$/ day. For low plant capacities, the MSF / RO cost ratios are more than two for both the capital and production costs. On the other hand, this ratio drops as the capacities increase. At a capacity of 75000 $m^3$/ day the MSF/ RO ratio drops to 1.10 and 1.35 for both capital and production costs respectively. Table 2 shows the capital and production costs estimated for RO and MSF units.

At this stage it is very important to note that the estimation of the operation or production costs is a very complicated process because many variables are involved. For example, the electrical power consumed by desalination units depends on their types, rated capacity and performance ratio. Again the RO membrane replacement rate may make them loose their economic advantage if it exceeds about 75% of the installed membrane capacity per year. Furthermore, MSF units required almost double the land area required by RO units for an equal discharge. However, land area was not taken into consideration in the economic analysis as it is not a limiting factor. Land costs in desert and arid regions, where desalination units are used, are cheap.

## 5. Conclusions

Environmental concerns are felt and acted upon more strongly in some parts of the world than others. However, increasing environmental concerns appear to be a commonly sheared reality. While the desalination industry has a strong history of environmentally safe operation; it is highly probable that increased regulation of concentrate disposal will occur in many parts of the world. The industry needs to anticipate the direction of environmental considerations.

**Table 2. Comparison of RO/ MSF costs**

| Capacity ($m^3/d$) | Capital cost ($10^6$ LE) | | Production cost (LE/$M^3$ ) | |
|---|---|---|---|---|
| | MSF | RO | MSF | RO |
| 3000 | 88 | 45 | 20 | 10.12 |
| 5000 | 92 | 55 | 18 | 9.18 |
| 10000 | 137 | 92 | 14 | 9.10 |
| 15000 | 175 | 100 | 12 | 7.42 |
| 20000 | 197 | 160 | 11.50 | 7.15 |
| 25000 | 250 | 206 | 10.90 | 6.75 |
| 30000 | 295 | 250 | 10 | 6.41 |
| 40000 | 375 | 320 | 9.18 | 6.27 |
| 50000 | 480 | 378 | 8.23 | 5.96 |
| 60000 | 550 | 480 | 8.10 | 5.73 |
| 70000 | 640 | 550 | 8.03 | 5.73 |
| 80000 | 720 | 640 | 7.80 | 5.67 |
| 90000 | 810 | 734 | 7.35 | 5.67 |
| 95000 | 850 | 750 | 7.29 | 5.53 |

There are several environmental concerns associated with the disposal of desalination concentrates and their mitigation in most cases is straightforward in a technical sense. There is capital costs associated with each disposal method and mitigation approach. Thus environmental issues must be considered at the early stages of plant design. Existing plants most also consider environmental issues.

Both RO and MSF systems under study showed similar concentrate characteristics with those of the MSF system giving more pollution effect. The RO system is more environmentally and economically efficient compared with the MSF system. It occupies less space; it has simple start/stop operation and is delivered in modules, so no need to shut off the whole plant for emergency or routine maintenance. RO systems are cost effective with regards to both capital and production costs compared with MSF system by a factor of about two for small capacities and drops to 1.25 for large capacities. Besides the economic and environmental advantages of RO, there are some benefits of RO over MSF such as:

1- The flexibility of RO in meeting various water and power ratios while maintaining maximum process efficiency.
2- Corrosion problems are much less in RO than in MSF, (Corrado et al., 2003).
3- Energy consumption is low in RO than in MSF.

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