Estimating the availability of a reverse osmosis plant

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Abstract: This paper presents an assessment of a reverse osmosis (RO) plant in Kuwait by analyzing its operational and downtime patterns. The plant is divided into main subsystems and the performance of each subsystem is derived. The overall performance of the RO plant was assessed from the performance of its subsystems. Assessment of the operational time of was considered to be more appropriate than other performance measure since the plant was deigned to operate continuously. The plant subjective assessment of failure probabilities of subsystems was made wherever detailed data were not available. The overall unavailability of the RO plant with and without is around 1.87 days/year and 0.9 days/year, respectively.

Keywords: Performance measures, operational time, availability, failure probabilities

1. Introduction

Fresh water is essential for life and living species. Many countries have abundant fresh water supplies, while others have limited resources. The problem of the scarcity of fresh water supplies is apparent in the Gulf Cooperation Council (GCC) countries where fresh water resources are below poverty levels. In these countries, the fresh water demand has increased from 4.25 billion cubic meters (bm^3) in 1980 reaching 29.3 bm^3 in 2000, Ebrahim & Abdel-Jawad (1994). Therefore; desalination technologies have been used extensively in these countries to produce fresh water to cover the progressive increase in demand. The GCC region accounts for around 45 percent of total desalination capacity in the world, Parekh (1988). Commercially available desalination techniques are categorized into two types, i.e., distillation and membrane–based technologies. The distillation processes transform water into vapor then condense it into a liquid state. This process requires power in the form of thermal and electrical energy. Commercially available desalination techniques include multistage flash (MSF), multi-effect desalination (MED), and vapor compression (VC). Membrane–based desalination techniques consume power in the form of mechanical or electrical energy. Two processes under this category are commonly used, i.e., reverse osmosis (RO), and electrodialysis (ED). However, the latter is mainly for brackish water desalination. Although several desalination technologies are used in the GCC, MSF is dominant and it accounts for approximately 80 per cent of the world's plants.

RO has been considered a successful process for desalination of brackish water and seawater, Ebrahim & Abdel-Jawad (1994), Parekh (1988). The first major breakthrough in commercial application of RO came in 1975 when Dow Chemical, Du Pont and Fluid Systems developed large-scale RO modules for the Office of Water Research and Technology, USA. Considerable amount of interest and research in the RO process throughout the world has been in evidence since that time. Today RO is considered to be a powerful process for the removal of various dissolved solids, thereby generating the ultrahigh purity in water needed for the pharmaceutical industry, research laboratories, haemodialysis, etc. RO has also assumed a prominent role in freshwater production, because of its unique ability to remove ionic impurities, colloids, organic, microorganisms, and pyrogenic materials.

The most important subsystems of the RO plant are semipermeable membranes, filters, high-pressure pumps, feed-water pre-treatment system, and product-water post-treatment system (figure 1).

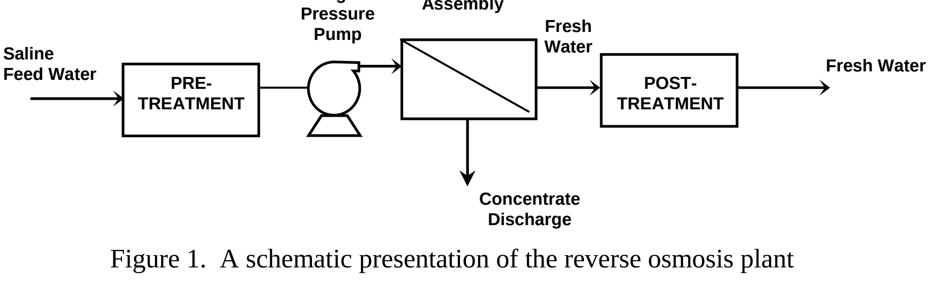

Figure 1. A schematic presentation of the reverse osmosis plant

The plant under study receives feed from either of the two beachwells located short distance from it. Each beachwell is fitted with a submerged pump; each of the pumps has a capacity of pumping seawater at a rate of 72 m^3/h. Before feeding seawater to the RO systems, it is pretreated to eliminate any coarse pollution matter and biofoulants. Additional treatments including chlorination, filtration and antiscalant addition, dechlorination are provided to ensure the long service of the RO module system. The design temperature is 25^0C (22^0C minimum and 35^0C maximum). Fine filtration is done through 5-μm cartridge filters in the final filtration stage. A high-pressure pump then pressurizes this high-purity filtrate to the required pressure level (60 to 65 bars) for the desalination process. Two types of RO membranes (one each for a train) are used, spiral-wound and hollow-fiber twin, each with a capacity of 300 m^3/d. The designed recovery rate has been fixed at 35%. The product water (i.e., high-purity water) is taken out at the end of the trains and sent for post-treatment (addition of minerals to make the water potable). The concentrated brine coming out from the system has a high pressure level (up to 50 to 60 bars). It is allowed to pass through the energy recovery system (a Pelton wheel turbine). The RO process is permanently monitored and volumetrically controlled to comply with the predetermined parameters. The membranes are cleaned at intervals depending on the actual service conditions; the cleaning/flushing equipment is made of suitable materials and comprised of a solution tank with motorized agitation, a pump, and cooling and heating facilities equipped with all necessary instruments such as temperature and pressure gauges and flow meters. The membranes are preserved with formaldehyde solution, if the shutdown period is longer than 4 or 5 days. Before the units are restarted, the formaldehyde solution is removed from the system and collected in the cleaning solution tank.

The pH of the product water is maintained at 7.5 to 8.2 by the addition of bicarbonate ions (using a dolomite/limestone dissolution filter). The equipment, materials, and instruments (except the membranes) have a working life of 20 years when working continuously (90% availability) or intermittently at variable outputs. The layout and control of the plant and equipment ensure easy operation and the use of minimum manpower requirements. The central control panel for the plant enables the operator to start and shutdown the plant partially or completely. For minimum breakdown, the design specifications for all the subsystems of the plant were reviewed. Since the plant was a new plant and several other research objectives were attached to the operation parameters and performance of the plant, only the parameters relevant to the project were reviewed.

In the RO process, the quality of feed is extremely important for the life of the RO membranes. The feed should be free from all suspended particles, and this is ensured by the filtration process. In the existing plant, the standby filters remove any possibility for failure due to malfunctioning of the online filter in the system. Hence for any future RO plant, it is recommended that standby filters be installed. The quality of seawater feed also determine the need for acid dosing, $NaHSO_4$ dosing and addition of antiscalant. Normally the failure of a system rarely occurs due to failures of the pumps used for these pretreatments of the feed unless human error intervenes in the dosing activity. The availability of the RO plant, therefore, greatly depends on the performance of the high-pressure pumps, membranes and their housings, various seals at all the junctions, and the dial gauges/indicators recording the various parameters. The thickness and material for the membrane housing should be chosen based on the maximum pressure obtained from the high-pressure pump and the desired safety factor level. Before housing the membranes, any crack or non-uniformity of thickness of the shell should be checked. The high-pressure pump should have the highest reliability; hence, selection of the pump should be made very carefully. There should be a proper preventive maintenance plan for the high-pressure pump to reduce the probability of its failure during operation. The membranes should be cleaned following the procedure recommended by the supplier. If membrane is cleaned from time to time, both the quantity of the product water increases and the membrane life improves. To obtain higher availability of the plant, all the important parameters like quality of feed, amount of flow, pH, feed concentration, feed temperature, SDI, high-pressure pump outlet pressure, RO feed pressure, and brine pressure, should be monitored at regular intervals. Should any parameter drift from the desired value, the plant operation should be stopped; otherwise damage may occur to the materials, equipment and workers in the plant along and a bad quality of product water may be produced.

2. Research objectives

The main aim of the work is to estimate the availability of the RO plant. The specific objectives are to:

- carry out a detailed survey of operating conditions and performance of materials, components, and subsystems of the RO plant;
- identify causes and sequences of failures in the RO plant; and,
- assess the failure rate of the RO plant by identifying the components and events causing downtime and unwanted effects.

3. Failure analysis

From the data recorded at the plant and from the design specifications of all the components and subsystems, it is felt that the failure of the RO plant many arise from failures of the beachwell pumps and the seawater feed line, the pretreatment process (chlorination, dechlorination, antiscalant addition, and pH control), cartridge filters, high-pressure pumps and motors, membranes, the cleaning/flushing system, the energy recovery system, the post-treatment system for the product water, valves (including leakage), instruments and controls, and various pipe lines. Failure could also occur from loss of the power supply and human error; however, these are not considered since these are independent from the RO technology.

Several safety analysis methods are used to assess the failure of a system. Failure Mode Effects and Criticality Analysis (FMECA) are considered as an important step in the risk and safety analysis study of a system. It involves reviewing as many components, assemblies and subsystems as possible to identify failure modes, critical failures and their causes and effects, Billinton & Allan (1992), Henley & Kumamoto (1992). It is mainly a qualitative analysis and is a very useful tool in suggesting design improvements to meet the reliability requirements. In this study, it was decided to go for a top-down approach, and the analysis was extended down to a level at which failure rate estimates were available from the data already collected.

Since the RO plant was a new plant, the construction of FMECA was hampered due to lack of enough data on failures, their causes and their effects. Statistically the estimation of the failure times of all the components and subsystems of the plant was very difficult in the absence of sufficient objective data. Hence, in a few cases, subjective assessment of failure times, causes and effects of failures has been made from the experience of the plant personnel. The data on all the special incidents noticed at the RO plant were recorded in the log book and analyzed for the FMECA of the RO plant in the following fashion:

- The RO plant was divided into its subsystems: beachwell, pretreatment of the feed, filtration, high-pressure pump, membrane system, energy recovery, and post-treatment of the product water and.
- The system's functional diagrams and drawings were reviewed to determine the interrelationships between the various subsystems.
- The operational conditions, which might affect the system's performance, were assessed and reviewed to determine the adverse effects that they could generate on the system.
- For each subsystem (and, if possible, for components), the operational and failure modes were identified and recorded. In addition, possible failure mechanisms, which might produce the identified failure modes, were also recorded.
- The mechanisms to detect a failure mode were then studied.
- From the available data, a failure rate assessment was made for each of the failure modes. (Unfortunately the data was not sufficient since only two-and-a-half years' data were available).
- The failure effects were ranked based on their importance, and critical failures were identified.

Event tree analysis (ETA) methodology is an inductive analysis. It starts with a specific initial event and follows all progressions of the accident and its contribution to the failure of other components, and subsystems. The probability of failure of the component/subsystem is calculated by tracing back and identifying the possibility of all accidents the let to it.

Fault Tree Analysis (FTA) is another method used in safety analysis. It is a deductive methodology for determining the potential causes of accidents, or for system failures more generally, and for estimating the failure probabilities. FTA is centered about determining the causes of an undesired event, refereed to as the top event, since fault tree are drawn with it at the top of the tree. It then proceeds downward, dissecting the system in increasing details to determine the root causes or combinations of causes of the top event. Top events are usually failures of major consequence, engendering serious safety hazards or the potential for significant economic loss.

FTA yields both qualitative and quantitative information about the system under study. Fault tree construction provides the analysts with a better understanding of the potential sources of failures, which will lead to rethink the design and operation of the system in order to eliminate many potential hazards. Once completed, the fault tree can be analyzed to determine the combinations of component failures, operational errors, or other faults that initiate the top event. Finally, fault tree may be used to calculate the demand failure probability, unreliability, or unavailability of the system under study. A FT is a diagram that displays the logical interrelationships between the basic causes of the failure. A few standard symbols, commonly known as gates, are used to depict the relationships between the events giving rise to the failure of the system. "AND gates" are used to connect the groups of events and conditions, if all of them are required to be present simultaneously to cause the hazardous event to occur; whereas "OR gates" represent the existence of the alternative ways in which a failure can occur.

4. Methodology

The aim of reliability and availability of any continuously operated system in industry is to produce the desired level of output on a continuous basis without failures and to restore the system into an operable state as early as possible whenever the system suffers from failure, Haimes *et al*. (1992). The management can achieve the lowest total costs possible, if reliability and availability are maintained at a high level. Reliability management of a system is a systematic approach to identifying and assessing the causes and frequencies of its failures, and reducing and/or controlling the effects of failures to provide the satisfactory performance of the system to the society, Bazovsky (1961). Component failures and human errors not only affect the performance of a system but they can also cause accidents. The frequencies of such events are assessed during the design stage of the system. In order to derive the maximum benefit, reliability analysis of such a system has to be made at the design stage and it should be carried on until the system is finally replaced. A fresh analysis may be recommended whenever there are modifications of the system. Since continuously operated systems can tolerate failures, the systems can be restored to an operational level by carrying out the required repairs and maintenance. For such continuous systems, a more appropriate performance measure is availability, which is defined as the probability that a system or component is performing its required function at a given point in time or over stated period of time when operated and maintained in a prescribed manner, Eblening (1997). It is classified under point-wise availability (i.e., availability at specific points in time), interval availability (i.e., availability for an interval of time) and inherent availability (i.e., long-run availability). For continuously operated systems, inherent availability is the most meaningful; it is a ratio of the total uptime (i.e. total operating time) to the total system time (i.e. sum of uptime and downtime). Availability takes into account not only the failure aspect of the system (reliability), but also the restoration of the failed components through repair or replacement (maintainability). Maintainability is a design feature, and appropriate considerations are required regarding this aspect for any continuously operated system. Since the total downtime is composed of the time for inspection and detection of faults, the time to repair faults, and administrative time, one can aim at minimizing each of these components to reduce the total downtime. Mathematical models have been designed to estimate the downtimes of systems, and researchers have approximated the downtime distributions as negative exponential distributions. If $M(\mathrm{t})$ represents the maintainability function and μ represents the mean down time, then $M(\mathrm{t})$ is given by

$$M(t) = 1 - e^{-\mu t} \tag{1}$$

If the time-to-failure distribution indicates the reliability of the system, and most commonly, exponential distribution is used for this purpose, the reliability function is given by

$$R(t) = e^{-\lambda t} \tag{2}$$

A detailed FT diagram was drawn for the plant using OR and AND gates, as shown in figure 4, Chaudhuri & Hajeeh (1999). The outputs of these gates in terms of the event unavailability were computed. Unavailability of the plant due to power supply disruption and human error was not included in the overall estimation of unavailability since these are independent of the RO technology. Consider the AND fault tree as given in figure 2 where simultaneous existence of the events $B_1, \ldots, B_n$ results in the top events. Thus, the system unavailability $Q_S(t)$ is the probability that all events exist at time *t* and is given by Equation 3.

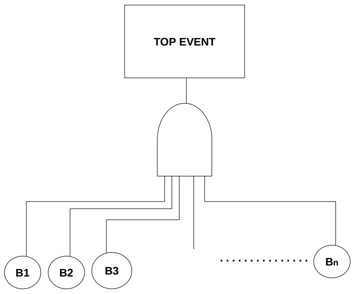

Figure 2. Gated AND fault tree

$$Q_s(t) = \prod_{i=1}^{n}(1 - Q_i) = \Pr(B_1 \cap B_2 \cap \ldots \cap B_n) = \Pr(B_1)\Pr(B_2)\ldots\Pr(B_n) \tag{3}$$

For an OR fault tree as given in Figure 3, the top event exists at time *t* if and only if at least one of the *n* basic event occurs at time *t*. Therefore, the system unavailability is given by Equation 4.

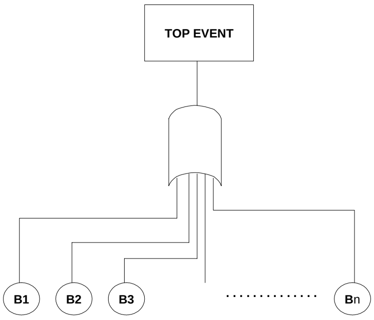

Figure 3. Gated OR fault tree

$$Q_s(t) = 1 - \prod_{i=1}^{n}(1 - Q_i) = \Pr(B_1 \cup B_2 \cup \ldots \cup B_n) = 1 - \{[1 - \Pr(B_1)][1 - \Pr(B_2)]\ldots.[1 - \Pr(B_n]\} \qquad (4)$$

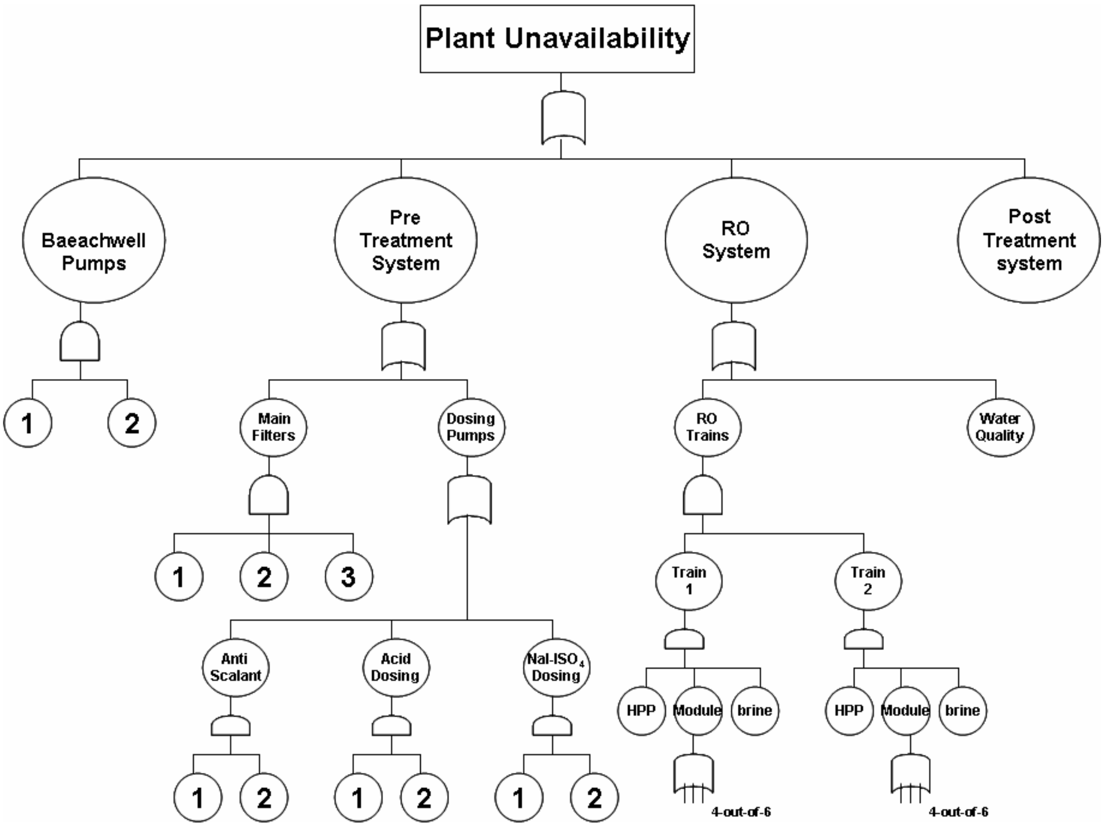

Figure 4. A FT diagram plant using OR and AND gates

5. Results and Discussion

Since the plant under study is new, small, and efficient, the unavailability (down time) is used as a performance indicator. The availability is calculated as

$$Q = 1 - A = \frac{Downtime}{Uptime + Downtime} \qquad (5)$$

Since the plant was new, and statistical assessment of failure and repair rates was difficult due to the lack of data, system availability was computed as a ratio of the time the system was working satisfactorily and the total system time.

No	Sub-System		Formula	Unavailability (Q)
1	Beachwell pumps (bwp):	1 operated , 1 standby	0.1262×10^{-3}	0.00013
2	Main filters:	1 operated, 2 standby		0.00000
3	Dosing:			
	Antiscalant	1 operated, 1 standby	0.2314×10^{-4}	0.00118
	Acid	1 operated, 1 standby	0.1134×10^{-2}	
	$NaHSO_2$	1 operated, 1 standby	0.2314×10^{-4}	
4	High-pressure pumps (HPP):			
	Train 1			0.03393
	Train 2			0.02985
5	Energy recovery turbines (ERT):			
	Train 1			0.03065
	Train 2			0.03107
6	Reverse osmosis system:			
	- Without ERT			0.00118
	- With ERT			0.00381
Plant overall unavailability (Q_{plant})*:				
	- Without ERT			0.002318(0.9days/year)
	- With ERT			0.005113(1.87 days/year)

***** $Q_{plant} = 1- (1-Q_{bwp})(1-Q_{pre\text{-}treatment})(1-Q_{RO\ system})$

Table 1. Unavailability for the different sub-systems for the RO plant

6. Conclusion

The reverse osmosis (RO) process is one of the major processes for producing potable water from seawater through desalination. The performance of any RO plant depends on the failure behavior of its subsystems. Since RO plant is to be continuously operated with minimum amount of down time, the reliability of the subsystems is to be maintained at high level by proper design and selection of materials of these subsystems. Standby redundancies are needed for the subsystems, which are critical in nature and whose failures will cause the entire plant to stop. Since RO plants are likely to show very high availability, operation of a parallel combination of a few RO plants can become a viable alternative to other desalination plants used in the middle-east countries. Design and installation of RO plants for desalination of seawater are recommended for the region because it has high performance and economical. Future research should attempt to compare the performance of RO technology with other water desalination technology such as multi stage flash (MSF), which is extensively used in the region.

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