Failure Analysis of Reverse Osmosis Plants

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Abstract: – Water resources in Kuwait are very scarce and do not meet the ever growing demand. To satisfy this colossal water demand and to compensate for the shortage of freshwater, the government has constructed desalination plants. Water desalination processes separate dissolved salts and other minerals from water from brackish, and seawater to produce water suitable for human consumption or irrigations. Reverse Osmosis (RO) is a proven technology for desalinating seawater; it is pressure driven membrane processes.

The analysis in this work enfolds an assessment of the performance of a small reverse osmosis plant with and without an energy recovery pelton wheel turbine. The data collected are from an experimental RO plant in the region; these data are concerned with the failures of several components and subsystems of the plant over a 4-year period of continuous operation. Using fault tree technique the long term of the system is obtained by calculating the unavailability of the different subsystems. Since the plant is designed for continuous operation; the operational time was used to assess the performance of the plant

Key words; Energy recovery system, Availability, Failure probabilities, Operational time

1 Introduction

Energy and Water and are the essential elements for the development of modern societies; Water is essential for the existence of life on the plant, and fresh water constitutes only 3% of the water available on earth. Therefore, man countries suffer fresh water scarcity. Many countries in the Middle East, especially the Arabian Gulf countries such as Kuwait have limited fresh water resources. The GCC countries have resorted to water desalination to satisfy their water demand. Kuwait is an arid country, rich in oil resources, but poor in natural water resources it is bordering the Arabian Gulf. Kuwait is a rich, oil- producing country with a gross domestic product (GDP) of around $123 Billion.

The country does not have significant natural resources of freshwater. The average annual rainfall is only about 110 mm. The rate of freshwater consumption in Kuwait is one of the highest in the world (currently, over 600 liter per capita per day) and it is escalating at a staggering rate of about 7.9% annually. Such per capita levels of water consumption are considered excessively high, especially where there are limited agricultural and industrial activities [1]

Therefore, Kuwait relies widely on seawater desalination to meet the ever increasing demand; desalination is a process of separating dissolved minerals from saline water. Multi-Stage-Flash (MSF) is the desalination process largely used in Kuwait for the last 40 years. It is an established technology and is combined with co-generation of electricity. However, one of the main shortcomings of MSF is it's highly energy consumption. However, Reverse Osmosis (RO) technologies have also been gradually adopted with some very large plants now in operation in the region.

The RO market has considerably increased during the recent years. The major factors affecting the cost of product water of RO plants are the power consumption and capital cost. A pictorial presentation of RO plant is exhibited in figures 1. The plant comprises a seawater feed source; a pretreatment module; a high pressure feed pump; an RO membranes rack; and a post treatment module. RO membranes are two types: spiral wound and hollow fiber [2].

The literature contains several articles pertinent to RO desolation plants. Examples are: Dejebjian et al. [3] examined the five year collected from an RO plant in Egypt to investigate the effect of the design and the operations conditions on performance of the plant. The findings confirmed the sensitivity of plant's performance to changes in feed water temperature, salinity and pressure. Meanwhile, Guozhao et al. [4] developed a simulated annealing algorithm to examine the optimal behavior of Small reverse osmosis (RO) driven by wind and solar energies. Integer and continuous variables in the optimization model of the hybrid schemes for a region of Iran are considered with the objective of finding and optimization function that minimizes the life cycle cost is used to evaluate different types of renewable energy systems.

The results are compared with those from original chaotic search and simulated annealing algorithms. Results demonstrated that, the hybrid renewable energy system decreases system cost and increases system reliability. Shahabi et al. [5] compared the cost and environmental impact using of two scenarios: an *open intake* in which a seawater reverse osmosis desalination plant uses an open intake, and a *beach well* in which feed water is obtained from the subsurface using beach well intake. Findings indicated that the beach well intake plant life cycle environmental burdens and cost were lower the open intake plant.

Feliu-Batlle· et al. [6] derived a multivariable mathematical model to assess the dynamics of an RO plant with a fractional-order robust controller. It was illustrated that these controllers outperformed the robustness achieved using *other* controllers. On the other hand, Atab et al. [7] developed using the Matlab software a numerical model based on solution-diffusion theory analyze the design and performance of an RO system in addition to measure the effect of feed water temperature, salinity, and pressure on the efficiency of the plant. Results revealed that with boosting recovery ratio from 30% to 60%, the specific energy of desalinated water production below 400 ppm was reduced from 2.8 kWh/m^3 to a more economically favorable value of is influenced by the feed water temperature and pressure.

Loutatidou et al. [8] assessed the capital cost of several actual commercial RO desalination plants in the Gulf Cooperation Council (GCC) countries and in five southern European countries. The parameters assessed include plant capacity, location, award year, feed salinity, and the cumulative installed capacity within a region. Findings indicated that the capacity of an SWRO desalination plant is the most important statistical parameter influencing the EPC cost of the plant.

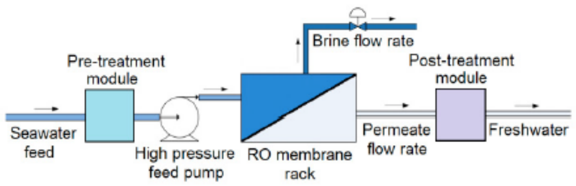

Fig.1 Elements of the Reverse Osmosis Desalination process

The RO plant under study receives feed from either of two nearby beach wells. . Each is installed with submerged pump; each of the pumps has a capacity of pumping seawater at a rate of 72m^2/h. The seawater is pre-treated before feeding to the RO systems, pre-treatment removes any coarse pollution matter and biofoulants. Additional treatments such as chlorination, filtration, along with the provision of antiscalant and dechlorination are to insure the extended service of the RO module system. The design temperature is 25^{o}C (22 ^{o}C minimum and 35 ^{o}C maximum). Fine filteration is done though 5-μm cartridge filters in the final filtration stage. A high pressure pump then pressurizes this high-purity filtrate to the required pressure level (60-65 bars) of the desalination process.

Two types of RO membranes (one for each train) –spiral-wound and hollow fiber twin-each with a capacity of 300m^3/d were used. The deigned recovery rate has been set at 35% the product water (high-purity water) is taken out of at the end of the trains and sent for pretreatment (addition of minerals to make the water potable). The concentrated brine coming out from the system has a high pressure level (up to 50-60 bars). It is allowed to pass through the energy recover system the system (a Pelton wheel turbine).

The RO process is permanently monitored and volumetrically controlled to comply with the predetermined parameters (Fig. 2)

Fig.2 Reverse osmosis desalination plant.

2. Failure evaluation and analysis

The main purpose of reliability analysis of as continuously operated system is to assure that the desired level of output is maintained at a continuous level without any failures. Reliability management of a system is an approach used to assess its performance and identify the causes and frequencies of its failures. Causes of failures could be system related or due to human errors [9].

Many of the continuously operated system systems such as the RO plant upon failure can be restored to an operational level buy carrying out the required repair and d maintenance; therefore in such cases availability is a suitable performance measure... Availability is defined as the probability of a system performing its intended function over a period of time [10].

Operating systems are subject to wear and tear, leakers, and ruptures and eventually malfunction; maintenance actions are necessary throughout the operation to restore the function of systems and delay failure. It is essential for the analyst to understand the reasons for accidents occurrences by assessing the reliability of the various components. The main approaches used include failure modes and effect analysis, block diagram, event tree analysis, and fault tree analysis.

Fault tree analysis (FTA) is used in this study to assess the performance of the system. Fault tree analysis is the *logical model* of the relationship of the undesired event to more basic events. In this method, a hierarchy is constructed where the top event is the undesired event, the middle events are intermediate events, and the bottom of the fault tree is the causal basic events or primary events.

The logical relationships of the events are shown by logical symbols or gates; the most used are the AND and the OR gates. The AND gate indicates the all succeeding events have to occur before a preceding event occurs, while the OR gate implies that for a preceding event to occur at least one subsequent event has to occurs (Henley and Kumamoto, 1994. The FTA for the RO plant under study is given in Fig. 3 below [11]...

3. Methodology

The RO plant is small and continuously operated, availability is more appropriate measure; it encompasses both relativity and maintainability. Due to the massive information collected on the plant, only the failure considered via unavailability. The formulas for both the availability/ unavailability are as follows:

$$A=\frac{Uptime}{Total\,time}=\frac{Uptime}{Uptime+Downtime}=\frac{MTTF}{MTTF+MTTR}=\frac{\frac{1}{\lambda}}{\frac{1}{\lambda}+\frac{1}{\mu}} \quad \textbf{(1)}$$

$$\tilde{A}=(1-A)=\frac{Downtime}{Total\,time}=\frac{Downtime}{Uptime+Downtime}=\frac{MTTR}{MTTF+MTTR}=\frac{\frac{1}{\mu}}{\frac{1}{\lambda}+\frac{1}{\mu}} \quad \textbf{(2)}$$

$$\tilde{A}=(1-A)=\frac{Downtime}{Total\,time}=\frac{Downtime}{Uptime+Downtime}=\frac{MTTR}{MTTF+MTTR}=\frac{\frac{1}{\mu}}{\frac{1}{\lambda}+\frac{1}{\mu}} \quad \textbf{(3)}$$

To find the unavailability of the RO plant, first the fault tree for the system is constructed. Derails are shown in Fig 3.

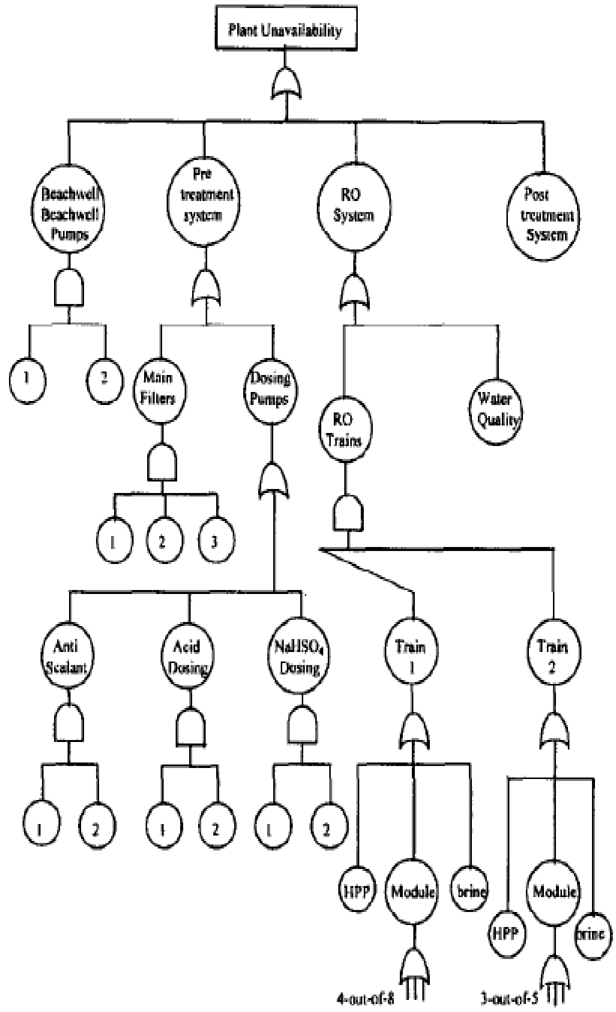

Fig.3 Fault tree diagram of the reverse osmosis plant.

The unavailability of the OR and AND gates are calculated as follows:

OR gate

$$\tilde{A}_s=1-\prod_{i\in x}(1-\tilde{A}_i)=1-\prod_{i\in x}\left(1-\frac{\frac{1}{\mu_i}}{\frac{1}{\lambda_i}+\frac{1}{\mu_i}}\right)$$

AND gate

$$\tilde{A}_p=\prod_{i\in x}(1-\tilde{A}_i)=\prod_{i\in x}\left(1-\frac{\frac{1}{\lambda_i}}{\frac{1}{\lambda_i}+\frac{1}{\mu_i}}\right)$$

4. Results and Discussion

The unavailability of the RO plant without the energy recovery system is calculated using the following relationships:

$$\tilde{A}_{Plant}(train1) = 1 - \begin{bmatrix} (1-\tilde{A}_{BP})*(1-\tilde{A}_{BT})*(1-\tilde{A}_{HPP}) \\ *(1-\tilde{A}_{RO}) \end{bmatrix}$$

$$\tilde{A}_{Plant}(train\,2) = 1 - \begin{bmatrix} (1-\tilde{A}_{BP})*(1-\tilde{A}_{BT})*(1-\tilde{A}_{HPP}) \\ *(1-\tilde{A}_{RO}) \end{bmatrix}$$

Meanwhile, the unavailability of the RO plant with the energy recovery system is calculated using the following relationships:

$$\tilde{A}_{Plant}(train1) = 1 - \begin{bmatrix} (1-\tilde{A}_{BP})*(1-\tilde{A}_{BT})*(1-\tilde{A}_{HPP}) \\ *(1-\tilde{A}_{ERT})*(1-\tilde{A}_{RO}) \end{bmatrix}$$

$$\tilde{A}_{Plant}(train\,2) = 1 - \begin{bmatrix} (1-\tilde{A}_{BP})*(1-\tilde{A}_{BT})*(1-\tilde{A}_{HPP}) \\ *(1-\tilde{A}_{ERT})*(1-\tilde{A}_{RO}) \end{bmatrix}$$

Since the plant was designed for continuous operation, assessment of the availability of the plant was considered to be more appropriate than that of reliability. As mentioned previously, a four year data are examined thoroughly for the performance of the various subsystems of the plant. Results are shown in Table 1. Afterwards, the unavailability of the systems is computed for the plant with and without energy recovery system. Moreover, two scenarios are considered, in the first scenario, Train I is chosen and train 2 was disregard, in the second scenario the roles where switched.

Table 1. Unavailability of the RO plant subsystems

Sub-system	Status	Unavailability
1. Beachwell pumps	1 operated 1 standby	1.262×10^{-2}.
2. Min Filters	2 operated 1 standby	0
3. Pretreatment: Dosing Acid $NaHSO_2$		 2.314×10^{-3} 1.134×10^{-3} 1.134×10^{-3}
4. High-pressure pumps (HPP) Train 1 Train 2		 0.03393 0.02985
5. Energy Recovery turbines (ERT) Train 1 Train 2		 0.03065 0.03107
6. Reverse osmosis Train 1 Train 2		 0.01596 0.07957

Next, the overall unavailability for both scenarios are determined for the different cases (Table 2)

Table 2. Availability and unavailability of the plant

RO Trains	Unavailability		Availability	
	With Energy Recovery Turbine	Without Energy Recovery Turbine	With Energy Recovery Turbine	Without Energy Recovery Turbine
1	0.080	0.050	0.920	0.950
2	0.136	0.108	0.864	0.892

5. Conclusions

Among the various processes, membrane desalination via reverse osmosis (RO) has become the most widely used solution, as it is generally the least costly. It is particularly suited in countries under water stress and with limited energy resources.

Since the objective is to minimize the downtime of RO plant under study, the reliability has to be maintained at highest level by designing it at high level and use the top materials for the different subsystems. Additionally, subsystems redundancy is critical because any failure in this system will stop the whole plant.

Analysis indicated that the inclusion of an energy recover turbine lowers the availability of the system besides being costly. Future work should investigate the performance of the plant using various combinations of trains 1 and 2.

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