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Evaluation of the Existing Maintenance Policy for the Seawater Reverse-Osmosis Plant at Kuwait Bay Based on the Degradation Characteristics of Membranes

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Abstract

To address global water scarcity, desalination technologies have been developed and applied. These technologies are divided into thermal and membrane-based desalinations by separation mechanism. Reverse-osmosis desalination is the technology that is used most widely worldwide. Preventative maintenance of the membrane should be performed. However, this does not always occur for several reasons. This paper presents a procedure to analyze the effectiveness and efficiency of such maintenance by comparing proposed and existing maintenance points. Additionally, a case study of the seawater reverse-osmosis plant at Kuwait Bay was performed to demonstrate the procedure. Performing maintenance is particularly important to prevent failures that cause a system shutdown. Thus, it was confirmed that estimating the maintenance points by the proposed procedure was effective. In this respect, achieving decreased operating costs and improving operation efficiency, such as availability, can be expected if a suitable maintenance policy is established.

Keywords: degradation analysis, maintenance; membrane, seawater reverse-osmosis plant.

INTRODUCTION

Freshwater is an essential prerequisite for sustaining and developing human society. Additionally, the global demand for water has increased gradually, based on population and economic growth. For this reason, mankind has been confronted with the problem referred to as “water scarcity” for several decades. In particular, water scarcity has become more serious in the Middle East, parts of Asia (Central Asia, South China, India, Pakistan), America (the western United States, Argentina, Chile), Australia, and North Africa [1-4].

To address global water scarcity, desalination technologies have been developed and applied. These technologies are divided into thermal and membrane-based desalinations by separation mechanism. Additionally, desalination technologies based on membranes can be classified into three types: reverse osmosis (RO), nanofiltration (NF), and electrodialysis (ED) [3]. These membrane types each have degradation characteristics based on the operating conditions. In addition, maintenance points are determined by when the degradation characteristics reach predetermined criteria according to the related degradation mechanisms. Some research on the degradation mechanism of membranes has been reported. For example, Kang et al. [5] proposed suggestions for improving a polyamide RO membrane over its lifetime by examining the degradation mechanism and performing hypochlorite exposure experiments. In addition, Simon et al. [6] investigated the impact of chlorine exposure on membrane degradation. Antony et al. [7] also assessed accelerated degradation of RO membranes based on the salt rejection values and Fourier-transform infrared spectroscopy.

RO desalination is the most widely used technology worldwide. Although the Middle Eastern market was dominated by thermal processes due to low energy costs (fossil fuel-based), RO still has a major market share [3,8]. When low-grade thermal energy sources are used, the use of RO can be a very cost-effective decision [9]. The efficiency of operation for membrane-based desalination plants and RO plants has been studied. Zhu et al. [10] compared single-pass and two-pass membrane desalting operations to compute optimal operating points based on energy consumption. Bartman et al. [11] developed an optimal strategy based on optimization for an RO desalination system using a non-linear model. Drendel et. al. [12] assessed process design of RO facilities to maintain system condition within projected operational life based on feed water quality. Abraham and Luthra [13] determined the efficiency of a photovoltaic (PV) RO in India by comparing energy costs of PV with a diesel generator and applying Indian population-based information. Additionally, optimal strategies for the cleaning and replacement of membranes have been developed to reduce operating costs [14-16].

Several factors affect the desalination water costs, such as energy, maintenance, chemicals, labor, and replacement of membranes [17]. Indeed, the maintenance and replacement of membranes are major factors in reducing the total operating cost of RO desalination plants [17,18]. Plans for them can be determined in the annual plan and the membrane conditions, such as differential pressure (DP) and flow.

The maintenance of membranes should be performed preventatively. However, this does not always occur for several reasons, such as the conditions and plans for other equipment as well as changing conditions of the membrane from moment to moment. Additionally, a poor maintenance plan that is too late – or early – can cause loss of availability and cost efficiency [19]. Preventing a bad plan requires some prediction of maintenance times. Thus, in this study, we compared the real operational history and estimated maintenance points by degradation analysis to assess the existing maintenance policy of an RO plant.

METHODS

Membrane at the SWRO Plant at Kuwait Bay

Seawater reverse-osmosis (SWRO) plants are installed to produce fresh water from the sea in regions where fresh water is scarce, and consist of pretreatment facilities and pumps as well as the RO membrane itself [20]. The RO membrane is used to remove salt from seawater [21]. However, the membrane is readily fouled by mineral deposition, organic matter, the deposition of clay, and chlorine (Cl) due to the nature of its very thin film. Such fouling reduces the lifetime of the RO membrane. Thus, effective management of the membrane is strongly related to quality of the fresh water produced and the operating costs [17,18,22]. To prevent fouling, factors related to its occurrence should be controlled by filtering in pretreatment facilities among the components of an SWRO plant. Additionally, the pump, such as a typical high-pressure pump (HPP), that supplies pressure and water to the membrane must function smoothly.

Maintenance activities for the RO include cleaning in place (CIP), flushing, and replacement. These are performed if values of factors collected by the system or manual methods reach threshold values. The membrane is cleaned and washed using chemicals (CIP) and water (flushing). Replacement is performed when the membrane becomes disabled. Details are shown in Table 1.

Table 1: Membrane maintenance activities

Maintenance activity	Descriptions
CIP	A method of cleaning by passing a cleaning liquid through the system without decomposing the membrane Cleaning of contaminants such as silt, colloidal material, organic or inorganic substances, and scale on the membrane surface due to long operation periods.
Flushing	As a method of physical cleaning, pressing clean water into the membrane and draining contaminants by flow along the membrane surface.
Replacement	When the performance of a membrane falls below the reference value, replace one or more.

In this study, data collected for 50 months (2011 to 2016) except shutdown periods were used for the degradation analysis. A shutdown was performed annually for maintenance of the SWRO and lasted approximately 1 month. Degradation factors for maintenance activity were normalized flow, DP, and salt rejection, data regarding which were collected by a distributed control system (DCS) [7,23]. Thus, maintenance points were determined by guidelines based on these three factors. The guidelines for CIP are given by manufacturer of the membrane (Table 2). Additionally, a case study was performed with the operation history of the SWRO plant at Kuwait Bay in Section 3.

Table 2: Guidelines for CIP

Reference factor	Guidelines
Normalized flow	Less than 15% from initial normalized flow (the initial normalized flow: 623, the reference value: 529.55)
Normalized DP	More than normalized DP guide: 2.535 bar
Normalized salt rejection	More than normalized salt rejection guide

Study Procedure for Maintenance of the Membrane

The procedure used to analyze the effectiveness and efficiency of the maintenance of the membrane by comparing the existing and proposed maintenance points is shown in Figure 1. In the first step, representative degradation characteristics (normalized DP, flow, salt rejection) of the membrane were selected and gathered by the DCS. Then, data sets were extracted with splitting along the maintenance interval from the observed data without distinguishing maintenance activities (CIP, flushing, replacement). For example, a maintenance interval can be defined as CIP to CIP, CIP to flushing, or replacement to flushing.

Linear, power, exponential, and log models are used widely in degradation paths classified with increases or decreases over time. In this study, they were applied to fit the degradation models of extracted data sets based on the smallest sum of squared error (SSE). Parameters of the determined model were estimated and used to calculate degradation points for each data set. Moreover, data sets were divided into two types. One includes a threshold value and is used below the threshold value, and the other does not include a threshold value and is used for all data. Finally, the existing maintenance policy for the RO membrane was assessed by comparing the real operation history with the estimated maintenance from the viewpoint of the maintenance interval.

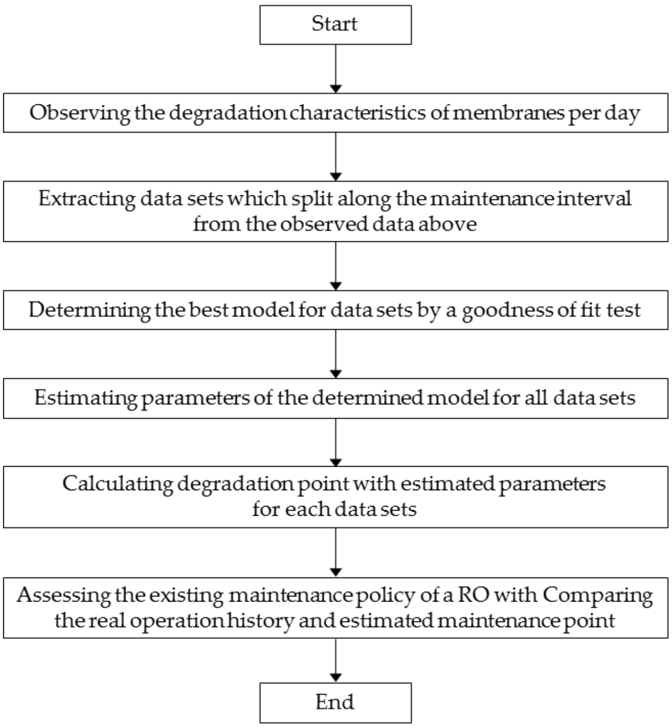

Figure 1: Procedure of this study

Degradation Analysis

Failure data should be demanded as essential information to estimate the lifetime of a unit and/or a product for which the lifetime is still unknown. However, technological advances have led to it becoming common to have little or no failure data, which makes the estimation of lifetime more difficult.

Some products have their own characteristics related to physical or performance degradation. These measures are called degradation data. Such degradation data make it possible to use degradation models and to derive inferences and predictions about lifetime. A degradation analysis can be used effectively when lifetime estimation using failure data is unavailable [24].

Let y denote the measurement of the degradation in the product. The measurement of y_i at time point t_i can be modeled as:

$$y_i = \eta(\alpha, \beta, t_i) + \epsilon_i, i = 1, \dots, n \quad (1)$$

where α is a constant, β is a slope parameter, t_i is the ith observed point on the measurement y, η is a degradation function which describes the degradation path, and ϵ_i is an independently and identically distributed random variable with mean zero and variance σ_ϵ^2 [25,26]. In the degradation analysis, a unit is considered to fail if its degradation level reaches a critical level (η_c). Thus, the elapsed time t to estimated failure is the lifetime of the unit [27].

$$\eta(\hat{\alpha}, \hat{\beta}, t) = \eta_c \quad (2)$$

Least-squares estimation (LSE) in the degradation analysis is a parameter estimation method to minimize the error between the measurement y_i and degradation model η (estimated value). Parameters of the degradation model, such as α ̂and β ̂, can be estimated by LSE. Additionally, because a power, exponential, and log model are converted to a linear model by log transformation of dependent and/or independent variables, parameters of all degradation models that were used in this study could be calculated by LSE. Equation (3) is a linear model and parameters of the linear model can be estimated with equation (4).

$$y_i = \alpha + \beta t_i + \epsilon_i \quad (3)$$

$$\text{minimize} \sum_{i=1}^{n} [y_i - \alpha - \beta t_i]^2, i = 1, \dots, n \quad (4)$$

RESULTS

Pre-Failure Analysis

To assess the existing maintenance policy, the real operating history (actual maintenance points, AMPs) was compared with recommended maintenance points (RMPs) according to the guideline criteria. The AMP is based on maintenance intervals (CIP to CIP, CIP to flushing, etc.), and is censored if shutdown is included in the maintenance interval. The RMP of degradation characteristics is defined as

i) If values of the degradation characteristics (normalized DP, flow, salt rejection) exceed threshold values of the guidelines within a maintenance interval, a point (or time) is considered the RMP.

ii) If maintenance was performed before reaching at threshold value, the maintenance point is considered a time-censored RMP.

Life distribution analyses on exponential, Weibull, and log normal distributions were performed to find the probability distribution that best fitted the two maintenance data sets (AMP and RMP). Generally, a fitness distribution was determined by the Anderson-Darling (A-D) method, a goodness-of-fit test method. A smaller A-D value means a better fit of the distribution. As a result, the log normal distribution was selected for both the AMP and the MP data of the membrane. Figure 2 shows how the data fitted with the distributions based on their cumulative distribution function (CDF).

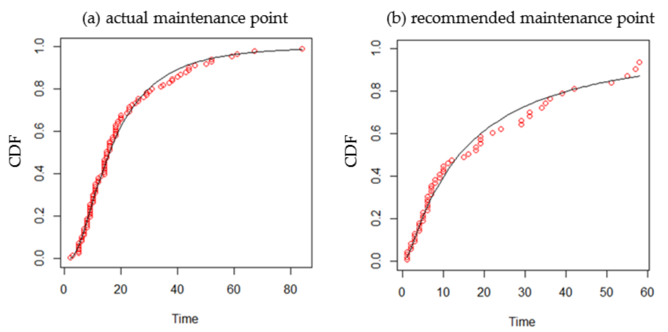

Figure 2: Cumulative distribution functions of (a) actual maintenance points and (b) recommended maintenance points of the membrane based on log normal distributions Procedure of this study

Additionally, mean time between maintenance (MTBM) and B_10 life were considered as representative measures of the maintenance interval. B_10 means the value of the independent variable corresponding to 10% of CDF. The MTBMs of the AMP and the RMP data were calculated as 21.733 and 28.153 days. The B_10 values were estimated as 6.149 and 3.768 days, respectively (Table 3). Furthermore, the MTBM and B_10 of the RMP were, respectively, larger and smaller than the AMP. As a result, examining the probability density function (PDF) and CDF of the fitted log normal distribution for the AMP and the RMP, the distribution of the RMP was wider than the AMP (see Figure 3).

Table 3: Analysis for maintenance intervals (AMP and RMP)

Type	Distribution	MTBM (days)	B_{10} maintenance (days)
AMP	Log normal distribution	21.733	6.149
RMP	Log normal distribution	28.153	3.768

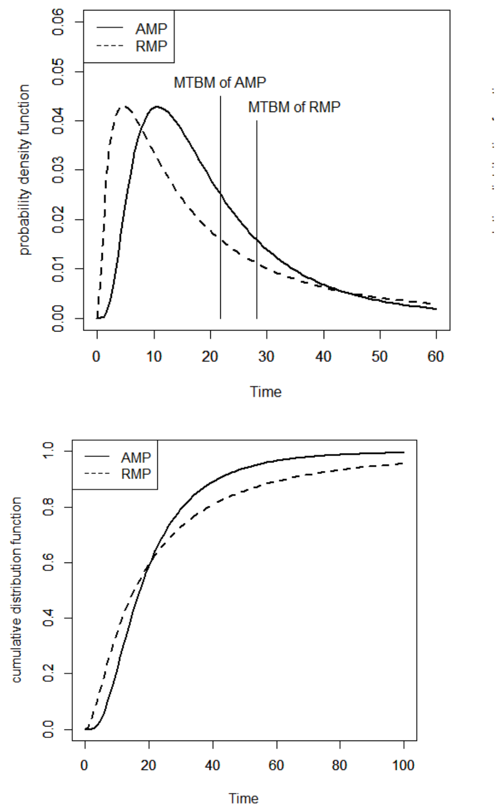

Figure 3: Comparison with the fitted distributions of AMP and RMP

Accordingly, the existing maintenance policy (AMP) did not reflect that time points of maintenance for the membrane were demanded randomly. For example, the membrane may last much longer, but maintenance had already been carried out. In the other case, the maintenance was performed later, even though earlier maintenance was demanded according to the guidelines. This poor maintenance policy can lead to increased costs and reduced operation efficiency. Thus, it is important to predict maintenance points exactly.

Degradation Analysis of the Membrane

In this study, the observed data sets, in total, 105 from a couple of the RO trains, were gathered and extracted with the procedure above. The degradation values of the data sets were determined per day without maintenance periods. As normalized salt rejection data were incomplete, they were not used. Thus, normalization DP and flow were applied to fitting and estimating the degradation models. In addition, the following data sets were removed to perform the degradation analysis:

i) RMPs are not included (e.g., maintenance was performed before the degradation characteristics reached the guideline criteria).

ii) The observed degradation characteristics of each data set have fewer than three values.

iii) The degradation characteristic increased over time, but the slope of the degradation model for a data set was negative.

As a result, 41 data sets were considered after this data preprocessing. The purpose of the degradation analysis is that the maintenance points be correctly predicted in advance when performing the maintenance activities immediately. According to this purpose, the chosen data sets were analyzed individually by ratios (25%, 50%, 75%). That is, a 100% ratio is from re-operating time to the time when the guideline criteria were reached for each data set (see Figure 4). In addition, the first observed value of the data sets was assumed to be '1' in terms of time.

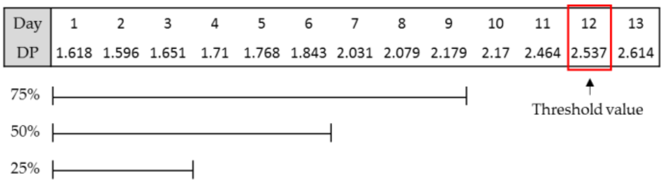

Figure 4: An example of a degradation data set and censored data set based on the ratios

Each degradation model of the normalized DP and flow was determined by mean squared error (MSE). A degradation model of the DP was fitted to the exponential model that had the lowest MSE value among the four models. Moreover, the linear model was selected for the flow by the same token. Details are shown in Table 4.

Table 4: Ranking of degradation models for normalized DP and flow by MSE

Rank	Linear model	Power model	Exponential model	Log model
DP	2	3	1	4
Flow	1	4	2	3

In terms of normalized DP, 41 data sets were analyzed with the exponential model and it was confirmed that most of them fitted well. However, a few data sets showed that the accuracy of estimated RMPs was markedly reduced. Figure 5 shows the result of the degradation modeling using up to 75% of the data. As the ratio increased steadily, the accuracy of the estimated RMP improved. Thus, this issue should be resolved if the amount of observed data is increased. This analysis was also performed to predict more accurately the estimated RMPs in terms of the normalized flow using the linear model.

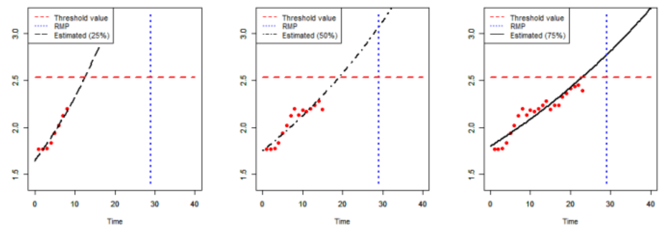

Figure 5: Example of degradation paths based on the ratios in terms of the normalized DP using (a) 25%, (b) 50%, and (c) 75% of the data set

Comparing Actual and Recommended Maintenance Points

To compare the accuracy of AMPs and estimated RMPs by the degradation analysis, the errors for RMP were calculated: $\varepsilon_{AMP} = y_{RMP}\text{-}y_{AMP}$ and $\varepsilon_{ERMP} = y_{RMP} - \widehat{y_{RMP}}$, where ε_{AMP} is the error in AMP, ε_{ERMP} is the error in the estimated RMP, y_{RMP} is the value of RMP, y_{AMP} is the value of AMP, and $\widehat{y_{RMP}}$ is the value of estimated RMP by the degradation model.

The closer the errors are to 0, the more ideal the model is. Figure 6 shows each error value for the AMP and the estimated RMP. The ε_{AMP} was distributed mainly below the center line. In contrast, the ε_{ERMP} was distributed above it (see Figure 6). Additionally, specific values of the errors indicated that the accuracy of the estimated RMPs was better than the AMPs in terms of simple sum, mean, and root mean square error (RMSE).

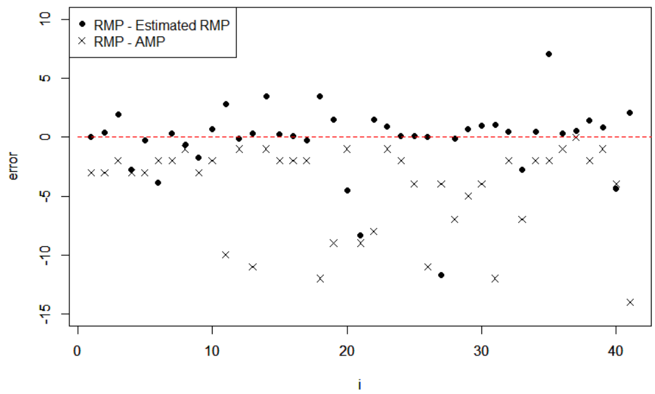

Figure 6: Distribution of the errors for AMP (x) and estimated RMP (dot)

Table 5: Comparison between AMP and estimated RMP by calculating sum, mean, and RMSE

Error	Sum	Mean	RMSE
$y_{RMP} - \widehat{y_{RMP}}$	-7.92	-0.193	3.048
$y_{RMP} - y_{AMP}$	-177	-4.317	5.715

Generally, maintenance activities should be demanded to restore the condition of the related system(s) and/or component(s). In particular, performing maintenance is very important prior to the failures that cause a system shutdown [28]. For this reason, the existing maintenance policy for the membrane of the SWRO plant is poor. Estimation of the maintenance points by the proposed procedure was effective for the same reason.

CONVLUSIONS

When maintenance is needed, it is important to perform it immediately in many industries with high operating risks. However, conventionally, maintenance has often been performed on the basis of operator experience. This can make the system (and/or plant) imperfect because such maintenance is implemented without considering the exact conditions of the system. The case study for the SWRO plant showed that it was unsystematic [28,29].

In this study, an existing maintenance policy was compared with maintenance using degradation analysis from the viewpoint of the efficient use of the membrane. The data sets used were from membranes of the SWRO plant at Kuwait Bay and were collected by DCS.

Two maintenance policies were compared: the existing maintenance policy (AMP) and the proposed policy (estimated RMP) by degradation analysis. The AMP policy was shown not to reflect random demands. This result means that the AMP policy is not optimal in terms of maintenance efficiency. To predict the exact maintenance point, a novel policy was proposed: the estimated RMP. Each model for the normalized DP and flow was assessed with exponential and linear models. The accuracy of the estimated RMP was higher than that of the AMP as a result of comparing the errors for the RMP.

In particular, it is vital that maintenance is performed before the occurrence of a critical failure. In this respect, the novel maintenance policy by the proposed procedure was effective. Accordingly, decreased operating costs and improved operating efficiency, such as increased availability, can be expected if a more appropriate maintenance policy is established.

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