Optimizing the Periodicity of Preventative Maintenance Inspection Based on Historical Reliability Data for Naval Steam Condensers

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Optimizing the Periodicity of Preventative Maintenance Inspection Based on Historical Reliability Data for Naval Steam Condensers

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Abstract

Condensers are critical to the operation of naval vessels that utilize the Rankine cycle for propulsion. Eddy current analysis is a nondestructive evaluation of the integrity of seawater tubes in condensers. Defects significant enough to be expected to allow seawater to leak into the steam side of the condenser prior to the next inspection are identified and plugged. In this paper, the interval between eddy current inspections is determined with a known probability of a tube leak occurring prior to the next inspection based on the results of past inspections. Ship maintainers will be able to optimize the inspection periodicity, thus reducing life-cycle maintenance costs within an acceptable risk. Condenser tube degradation is modeled along with eddy current inspection accuracy to determine the probability of a defect growing to a leak. A case study is presented that evaluates the impacts of inspection frequency and tube-plugging limit on the probability of a leak.

KEYWORDS: Maintenance, Steam Condenser, Markov model, Naval, tube failure, Optimization

Introduction

Naval vessels use copper–nickel alloys for seawater cooled shell and tube heat exchangers. The number of tubes in a heat exchanger can range from a couple dozen to several thousand. Copper–nickel alloys have good corrosion resistance along with being an excellent material for heat transfer (Ezuber, 2009). Of particular interest in this paper is the reliability of steam condenser tubes, which are cooled with seawater as the ultimate heat sink. Copper–nickel alloys are subject to corrosion, fouling, scale, and microbiological contamination (Robert D. Port Harvey M. Herro, 1993). Corrosion and microbiological contamination can lead to leaks that must be avoided due to the sensitivity of Rankine cycle components to seawater contamination. Maintenance practices are in place to inspect condenser tubes using eddy current analysis with the goal of identifying flaws before they become leaks (Koyama & Hoshikawa, 2007) and plug tubes that have a high probability of a flaw growing into a leak prior to the next inspection. Condensers are designed with excess cooling capacity to allow for tube plugging without impacting Rankine cycle efficiency.

Nomenclature

ϕ	Occurrence rate of a flaw
λf	Occurrence rate of a pluggable flaw given an existing flaw
λs	Occurrence rate of pluggable flaw with no previous indication
ρs	Occurrence rate of a leak without a previous indication
ρf	Occurrence rate of a leak given a reportable flaw
ρp	Occurrence rate of a leak given a known pluggable flaw
ω	Rate of inspection and tube plugging for flaws above the plugging limit.
S	Safe
F	Flaw
P	Plug
L	Leak

In this work, renewal process modeling is used to predict the failure of condenser tubes that undergo periodic inspections. The reliability model for copper–nickel tubes is developed using a Markov model. The goal of the developed model is to maximize the time between inspections while providing a very low probability of experiencing a leak during operations (Sakurahara et al., 2019). This model is expected to provide both a reduction in maintenance cost and maintenance time over the lifetime of the condenser. The reliability model begins with a general Markov model developed for pipes with an in–service inspection program and degrade to a leak before pipe rupture occurs (Fleming, 2004). The general model is adapted to condenser tubes with in–service inspection that entails an inspection of all tubes at a specific frequency. An action diagram of this specific model is developed in Innoslate and Monte Carlo simulations are performed to determine the probability of a tube leak occurring during the life of the condenser based on time before a condenser tube leak is experienced and the time between inspections.

Condenser Tube Failure Modes

Copper–nickel alloys are corrosion resistant in aerated natural waters (Bianchi, G. & Longhi, P., 1973). The corrosion resistance is largely due to the formation of a protective cuprous oxide (CuO_2) film on the surface of the tube (Tuthill, A. H., 1987; Ma, Jiang, Zheng, & Ke, 2015). Unfortunately, they also commonly experience problems with corrosion, fouling, scale, and microbiological contamination as a result of the water conditions. Although fouling and scale do not directly lead to flaws, they create non–uniformity on the surface of the tubes which can lead to concentration cell corrosion. Concentration cell corrosion occurs in areas where the liquid has different properties close to the tube wall (Robert D. Port Harvey M. Herro, 1993).

There are a number of corrosion mechanisms to which copper–nickel alloys are susceptible in seawater. Underdeposit corrosion occurs when deposits are present that are water permeable, and thus create a unique environment at the tube surface that is conducive to corrosion. Oxygen corrosion is a problem in highly oxygenated environments; however, oxygen corrosion is beneficial because it creates a protective layer of cuprous oxide (CuO_2) which inhibits further corrosion. Erosion followed by corrosion is another mechanism where the protective layer of CuO_2 is abrasively removed by the flowing fluid. Corrosion occurs at a higher rate in the absence of the protective layer. Galvanic corrosion can also impact copper–nickel alloys in seawater, which is an electrolyte, due to significantly different galvanic potential and a conductive pathway linking the materials (Robert D. Port Harvey M. Herro, 1993). The main source of galvanic corrosion in a well designed naval condenser is from sulfur contamination in the sea water (Taher, 2015). The presence of sulfur results in the formation of non-uniform sulfur rich films which replace the protective CuO_2 films in some areas leaving galvanically dissimilar materials in close proximity to one another. The sulfur contamination is often present in de–aerated seawater that has higher concentrations of hydrogen sulfide (H_2S) gasses. The final corrosion mechanism of significance is biologically–influenced corrosion. This occurs when biological materials contribute to the corrosion rate (Robert D. Port Harvey M. Herro, 1993) and have the nutrients (i.e. dissolved inorganic nitrogen) available in the water to survive (Melchers, 2015). Low level sulfide pollution in flowing aerated seawater promotes biologically–influenced corrosion (Hack, H.P., Lee, T.S., & Tipton, D.G., 1980) making it difficult to determine if the root cause for the galvanic corrosion is sulfides or biologically–influenced corrosion.

Corrosion Mode	Corrosion Rate (mmpy)	Source
Accelerated Corrosion	0.132	(Tuthill, A. H. & Schillmoller, C.M., 1969)
Localized Wall Thinning	0.020	(Taher, 2015)
Concentration Cell	0.102	(Tuthill, A. H. & Schillmoller, C.M., 1969)
Galvanic Corrosion	0.196	(Taher, 2015)
No Corrosion	0.002	(Powell, C.A. & Michels, H.T., 2000)

TABLE 1. Localized Corrosion Rates.

In this paper, the tube failure mechanisms that are modeled include: localized wall thinning, concentration cell corrosion, galvanic corrosion, and accelerated corrosion. These failure mechanisms were chosen because they are the most prevalent encountered in operating condensers. The model utilizes implicit consideration of physics in the probabilistic physics of failure model. In this case, the physical degradation mechanisms and influences are not modeled; rather, these are implicitly considered when determining the probability of each failure mode. (Sakurahara et al., 2019). This is intended to develop a more detailed mathematical model of corrosion, similar to Chookah, Nuhi and Modarres (Chookah, Nuhi, & Modarres, 2011), who developed a model of pitting and corrosion-fatigue mechanisms. Details of the conditions leading to corrosion of copper–nickel alloys are discussed by Metikos-Hukvic, Skugor, Grubac, and Babic; Ezuber; and Critiani, Perboni, and Debenedetti (Metikos-Hukovic, Skugor, Grubac, & Babic, 2010; Ezuber, 2009; Cristiani, Perboni, & Debenedetti, 2008).

The corrosion rates vary based on seawater chemical makeup, flow rates, lay-up processes, and cathodic protection. Typical corrosion rates were used for the model. Corrosion rates for copper–nickel tubes are normally between 0.02 and 0.002 mm per year with the corrosion rate decreasing to the minimum of 0.002 mm per year after the first 5 to 6 years of operation (Powell, C.A. & Michels, H.T., 2000). The localized rates range from 0.020 to 0.196 mm per year (mmpy) depending on the corrosion mechanism. Corrosion rates utilized in the model are shown in Table 1.

Eddy Current Analysis

Eddy current analysis is used for the nondestructive analysis of metallic structures. It has high detectability and inspection speeds while providing good discrimination (Abdalla et al., 2019). During eddy current analysis, a sensor with two coils, an exciter and a detector, is passed through the inner diameter of the tube. The sensor uses the remote field eddy current technique to detect the presence of flaws (Davoust, Brusquet, & Fleury, 2006). In Naval condensers, eddy current analysis quantitatively identifies the remaining wall thickness to evaluate condenser life expectancy and plan repair activities (Krzywosz, K., Tombaugh, R., Syverson, L., & Lozier, G., 1992). The probability of detection is normally determined by analyzing a large sample of data acquired from different types of defects and equipment combinations (Trepal, Liu, Lipetzky, & Salekeen, 2008). Typical eddy current procedures are capable of detecting cracks as small as 1.27 mm with a 99% detection rate (Ghoni, Dollah, Sulaiman, & Ibrahim, 2014). Although this is very accurate, the typical tube in a Naval condenser has a nominal wall thickness of 1.245 mm, which means the detection rate is below 99% for finding a pluggable indication. The eddy current detection rate is also influenced by the type of defect that is encountered in the tubing. Assuming a typical tube wall thickness of 1.245 mm, the lower detection limit for volumetric flaws is about 0.124 mm (10 % wall loss) and the lower detection limit for planar flaws and cracks is about 0.498 mm (40 percent wall loss) (Krzywosz, K. et al., 1992).

Eddy current analysis has a probability of detection (POD_A) that is dependent on the depth of the flaw being analyzed and accounts for the ability of the operator to identify the defect. Eddy current analysis is dependent on a trained operator to identify and analyze signal of interest as wall loss indications. For an indication with a wall loss of 0.871 mm (70 %), the POD_A is about 0.96 (Joo & Hong, 2015). Note that the POD_A is only for the calibrated defects for the type of probe used. Certain applications require the ability to detect a broader range of defects, like cracks in a transition region (Qi, Cui, Shao, Liao, & Zhang, 2019). For this paper, the POD_A will be held constant.

NAVSEA Technical Publication 2032 defines the reporting parameters for eddy current analysis of Naval ship heat exchangers (including condensers) (Naval Sea System Command, 2012). Based on this guidance, any indication of tube wall below 20 percent (80% or more original wall thickness remaining) is not a reportable defect. Therefore, eddy current indications that have a remaining wall thickness between 80 and 100 percent are considered safe. For a typical condenser, the goal is to identify indications that have wall loss greater than 0.871 mm (70%) and less than through wall (1.245 mm). The probability of detection for eddy current analysis is one factor in determining an optimum plugging limit.

For a given condenser, the plugging limit is determined based on the time between inspections, the probability of detection, and the consequences of a tube leak. In the ideal case, all indications above 70% through wall are plugged before they extend to a leak. In order to extend the time between inspections or reduce the probability of a leak during operations, the remaining wall depth that is used for the plugging limit may also be reduced from the nominal 70%.

Condenser Reliability Model

The cooling tubes of a condenser is a system that degrades during operation which can be characterized by a nonstationary stochastic process since the tubes deteriorate faster than they age (Shi, Xiang, & Li, 2019). Using this basis, a model of the corrosion of copper–nickel tubes with periodic inspection is developed to determine the optimum time between inspections. The inspections allow for flaws to be detected with eddy current analysis and those that are likely to progress through wall before the next inspection to be plugged. The Markovian method is useful to model this system because a tube cannot be in multiple states and the changes between states are characterized by constant transition rates (Modarres, 2018). The initial model utilizes a general Markov model to represent the condenser tubes "in a set of discrete and mutually exclusive states" (Fleming, 2004). The Markov model allows for the use of many years of in-service analysis data, accounts for the plug before leak methodology, covers the aforementioned failure mechanisms, and accounts for the uncertainty of eddy current analysis.

General Markov Model

As discussed in Fleming, a Markov model was developed to evaluate the impact of in-service inspection strategies for nuclear power plant piping systems. The model is used to evaluate a piping system that has four discrete states and is subject to failure (Fleming, 2004). The Fleming model was used as the basis for Figure 1 which shows a basic Markov model for condenser tube failures. Unlike a piping system, which has repairable flaws, the condenser consists of thousands of tubes which are plugged instead of repaired. The condenser is still operational after tube plugging, thus functioning the same way as a repairable piping system. The Markov model for condenser tube failures has four discrete states for a tube and represents all failure mechanisms. The states are named S - Safe, F - Flaw, P - Plug, and L - Leak. The states are defined based on the eddy current analysis where a tube in state S has no reportable defect. The state F is a tube that has an indication that measures above 20% through wall and below the plugging limit (70%). The state P is a tube that has an indication that measures at or above the plugging limit. The state L is a tube that has a leak and allows sea water to enter the shell side of the condenser. This state is undesired and is the purpose of having state P that models the plug before leak inspection methodology.

The state transition rates are given by:

ϕ = Occurrence rate of a flaw;

λ_f = Occurrence rate of a pluggable flaw given an existing flaw;

λ_s = Occurrence rate of pluggable flaw with no previous indication;

ρ_s = Occurrence rate of a leak without a previous indication;

ρ_f = Occurrence rate of a leak given a reportable flaw flaw;

ρ_p = Occurrence rate of a leak given a known pluggable flaw;

ω = Rate of inspection and tube plugging for flaws above the plugging limit.

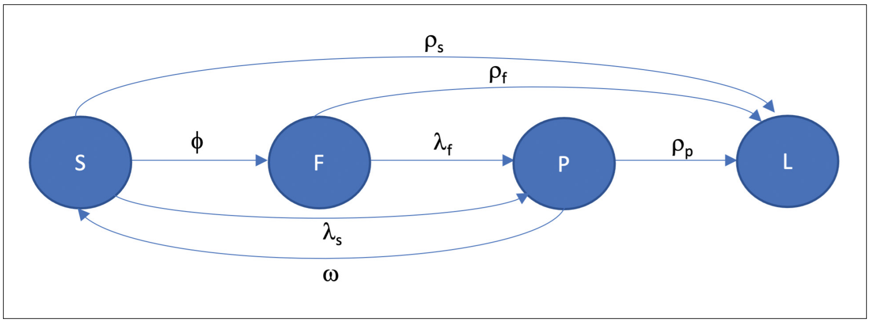

FIGURE 1. Basic Markov Model of Condenser Tube Failures.

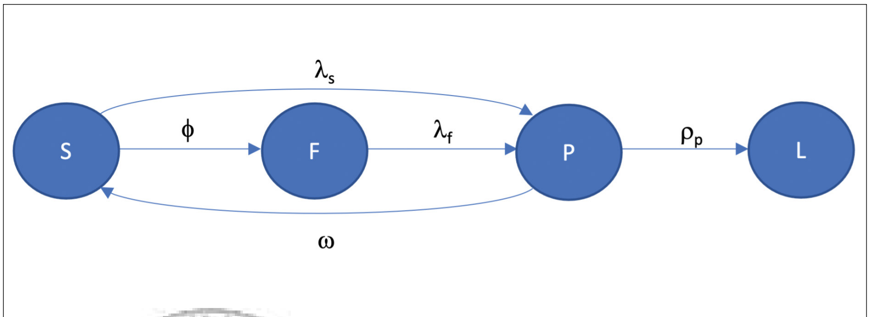

FIGURE 2. Reduced Markov Model of Condenser Tube Failures.

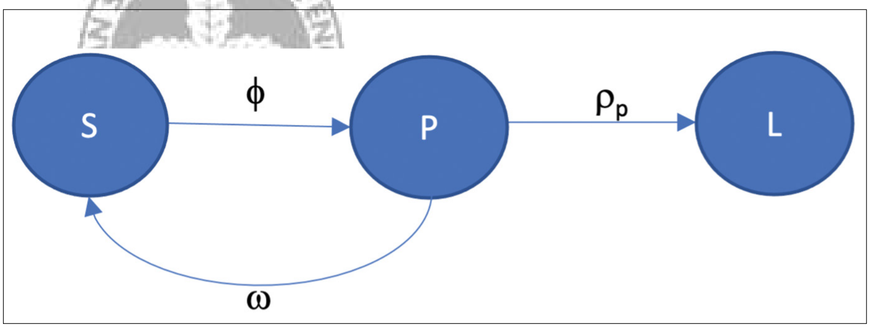

FIGURE 3. Markov Model of Condenser Tube Failures When All Tubes Are Inspected at Fixed Interval.

Plug Before Leak Markov Model

The Markov model shown in Figure 1 is simplified to represent the plug before leak methodology. The probability of bypassing the plug state is assumed to be zero so there is no probability of bypassing the plug state. A plugged tube is no longer in service, causing the state of the system to return to S. Therefore, ρ_s and ρ_f must be equal to zero. The Markov model is then reduced to Figure 2.

The process for condenser tube inspections does not depend on the existence of flaws. All of the tubes are inspected at the fixed inspection interval. No actions are taken if a tube progresses from the Safe state to the Flaw state. The only states that cause a response are Plug and Leak. This inspection process allows the further simplification of Figure 2 by removing the flaw state and associated occurrence rates. The simplified Markov model is shown in Figure 3 which results in a three state Markov model with only three occurrence rates.

Equations for each state

Differential equations are created for each state of the tubing as depicted in Figure 3. They are shown for each state in Equations (1) through (3). The sum of the differential equations is equal to one since the states are discrete as shown in Equation (4) (Fleming, 2004).

$$\frac{dS}{dt} = -\phi S + \omega P, \quad (1)$$

$$\frac{dP}{dt} = \phi S - (\omega + \rho_p)P, \quad (2)$$

$$\frac{dL}{dt} = \rho_p P \quad (3)$$

$$S(t) + P(t) + L(t) = 1 \quad (4)$$

Markov Model Parameters

ω represents the rate of tube inspection and plugging of flaws above the plugging limit. Condenser tubes are inspected at a set periodicity, T_{LI}. P_{FD} is the probability that a pluggable flaw will be detected in a tube when one exists. This value is equal to POD_A that is discussed earlier in the paper. Therefore, the rate of inspection and tube plugging for flaws about the plugging limit is shown in the following equation.

$$\omega = \frac{P_{FD}}{T_{LI}} \quad (5)$$

This equation is much simpler than that proposed by Fleming (Fleming, 2004) because the system is already shut down during the inspection, so the repair time is zero and 100% of the condenser is inspected, leaving the probability of inspecting a tube with a pluggable indication to be one. The parameters for the occurrence rate of a pluggable flaw (ϕ) and the occurrence rate of a leak given a known pluggable flaw (ρ_p) will be determined from in–service data. Further simplification of the model is accomplished by assuming a constant corrosion rate that is independent of the size of the flaw. That means that the rate of occurrence if equal as shown in Equation 6.

$$\phi = \rho_p \quad (6)$$

Solving for Leak Probability

Fleming showed a method to develop a time dependent state probabilities for a Markov model by determining the transition parameters and calculating the hazard rate through the solution of the differential equations (Fleming, 2004). This method requires deterministic transition parameters that are not known with any level of certainty. The simplification of the Markov model (Figure 3) lends itself to a probabilistic solution. The factors that influence the failure rate of the tubes are environmental, design, and operating (Modarres, 2018). There are a variety of reliability simulation and analysis tools available to determine this solution. This is typically done by inputting data reliability data into a program and determining the best fit distribution (Wessels, W. & Sillivant, D., 2015). One method is to use a hierarchical Bayesian analysis of the available data to estimate the failure frequency of tubes (Wang, Pandey, & Riznic, 2010). In this paper, due to the limited number of failures, the authors determined that a parametric analysis is necessary even with the potential for a high computational expense (Dempere, Papakonstantinou, O'Halloran, & Van Bossuyt, 2018). For the parametric analysis, a model-based systems engineering action diagram is developed to model the time dependent probability of reaching the leak state. The model-based system engineering software utilized for this solution is Innoslate, based on its wide access for academic work.

The simplified Markov model shown in Figure 3 has been created in Innoslate using an action diagram as shown in Figure 4. The Innoslate model utilizes the resource "wall thickness" and standard corrosion rates discussed previously to determine how many iterations or years are required to reach a leak state. The model assumes a constant annual corrosion rate for each failure mode and that the corrosion is acting in the same location in one tube each time that it occurs. Tube leaks typically result from localized accelerated corrosion as opposed to general wall thinning. The localized accelerated corrosion is an order of magnitude greater than general corrosion rate. Therefore, the modeling of corrosion occurring at a single point is a reasonable assumption for a conservative corrosion model since the leak state is typically only at one point in the tube. Additionally, in the Naval applications studied, the number of tube leaks that occur during the life of the condenser is less than 1%. The initial Loop "1.1 To leak state" determines if the wall thickness has reached the leak state and the projected life of the condenser. If the wall thickness reaches the leak state or the number of years (iterations of corrosion) exceeds the planned service life, the simulation is stopped. The number of times the "1.3 To Next Inspection" loop is allowed to iterate is based on the time between inspections in years and the "wall thickness" not getting to the leak state. Once either the number of iterations are achieved or the leak state is achieved, the loop will exit and then the "1.4 Corrosion to state plug" identifies if the wall thickness value is between the plug state and the leak state. If the wall thickness

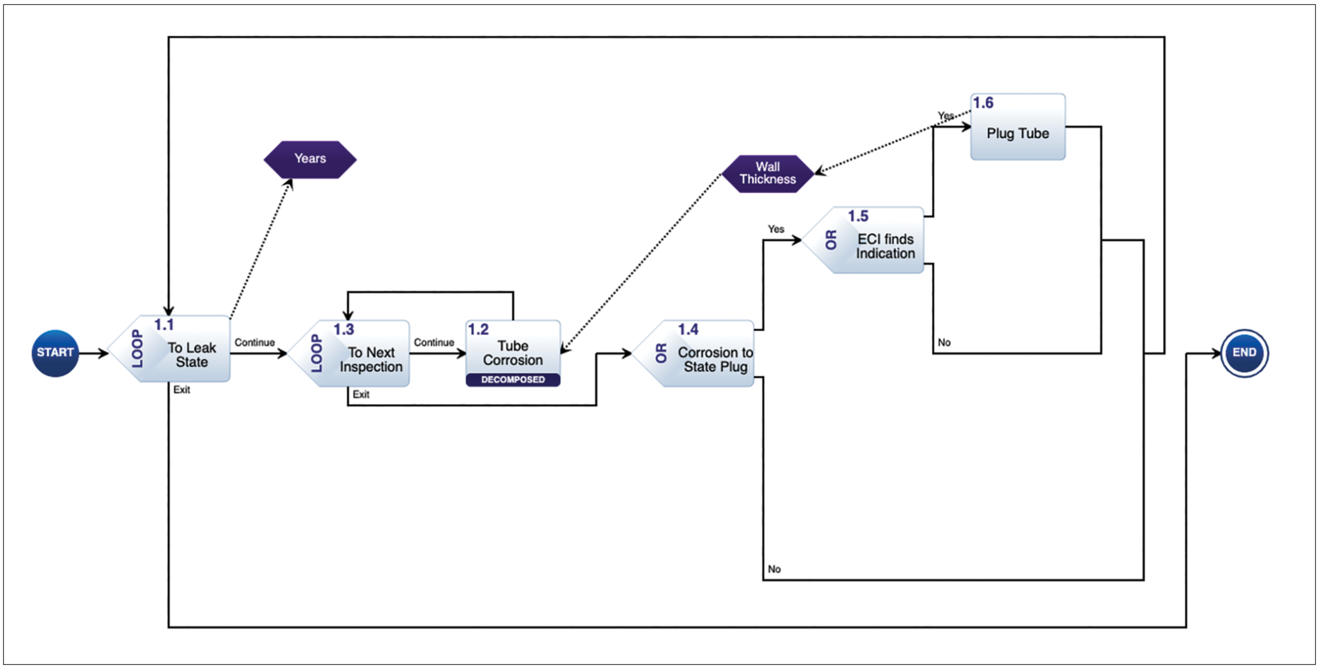

FIGURE 4. Innoslate Action Diagram to Model Corrosion.

value is in the range (wall loss ≥ 70% and ≤ 100%), then at "1.5 ECI finds indication" there is a 96% chance that the defect will be identified and plugged. If the tube is plugged, the wall thickness is reset to the success state. If ECI does not find the indication or the wall thickness value was not within range (wall loss < 70% or > 100%), then the loop returns to the "1.1 To Leak State." The model is simulated until the leak state occurs or the planned service life is exceeded. The number of times the "1.2 tube corrosion" action is executed simulates the number of years before a tube leak will occur.

The "1.2 Tube Corrosion" sub-diagram allows for different corrosion mechanisms to act on a tube using a constant annual corrosion rate for each mechanism. There is also a path for "No Measurable Corrosion," which indicates only minimal wall thickness has been lost during the year. The modeled corrosion mechanisms are shown in Figure 5. The factors that are varied in this action diagram are the relative probabilities of each failure mode. The percentages are determined by examining the number of tubes that are plugged and number of leaks that occurred using in-service data. The relative probabilities are used because there is limited in service data that identifies that actual corrosion mechanism or mechanisms that contributed to a pluggable indication. This is because the majority of tubes are plugged and left in place without failure analysis. A further limitation of the in–service data is that the operating environment of the condenser is not monitored. A monitored operating environment would provide insight into failure mechanism of the tube. Therefore, the relative probabilities of each failure mode are adjusted based on historical data. This provides the randomness of actual corrosion processes within the Innoslate action diagram.

Corrosion Mode	Relative Probability (%)
Accelerated Corrosion	2
Localized Wall Thinning	5
Concentration Cell	2
Galvanic Corrosion	1
No Corrosion	90

TABLE 2. Relative Probabilities of Localized Corrosion Occurrence.

Inspection Frequency (yr)	Plug State (%)	Leak Probability	Average Plugged Tubes
6	70	0.008% ± 0.007%	0.06
8	70	0.032% ± 0.020%	0.07
8	60	0.006% ± 0.010%	0.16

TABLE 3. Relative Probabilities of Localized Corrosion Occurrence.

Solution

The purpose of the model is to solve for the occurrence rate of a leak given a pluggable flaw (ρ_p) based on a chosen periodicity of inspection (T_{LI}). The simulation utilizes a Monte Carlo method with 5000 iterations. The high number of iterations minimizes the standard deviation of the number of times a leak occurred within the service life for a given inspection interval and plugging limit. The nominal service life of a condenser is set at 50 years and a probability of experiencing a leak is determined by identifying how many iterations ended at less than the service life. Each simulation was repeated 10 times to determine a range of probabilities for a leak during the service life of the condenser within a 95% confidence interval.

The first step in model set up is to identify the relative probabilities of each of the five corrosion modes in Figure 5. This was accomplished by comparing the results of the model with in–service data for leaks that occurred up to the current age of the condenser at an inspection. The values were varied until there was a best fit of the aggregate leak rate for 12 randomly chosen naval condensers. The aggregate leak rate is 0.008%. The relative probabilities for the best data fit are shown in Table 2.

To verify that values in Table 2 represent the probability of a leak occurring, the Monte Carlo simulation (5000 iterations) was repeated 10 times to achieve a satisfactory confidence interval. The simulations result in a probability of leak of 0.018% ± 0.013% at a 95% confidence interval. This range covers the observed leak rate of 0.008%. This value is based on a random sampling of Naval condenser data. The model also provides the number of tubes plugged during the simulated life of the condenser. This value under-represents the actual number of tubes that require plugging and results from the model simplification of having one tube experiencing corrosion at a time while in reality all tubes are exposed to a potentially corrosive environment. The Monte Carlo simulation is used to identify the probability of a tube moving from the plug state to the leak state (ρ_p) shown in Figure 3, not necessarily model the corrosion rate of all condenser tubes.

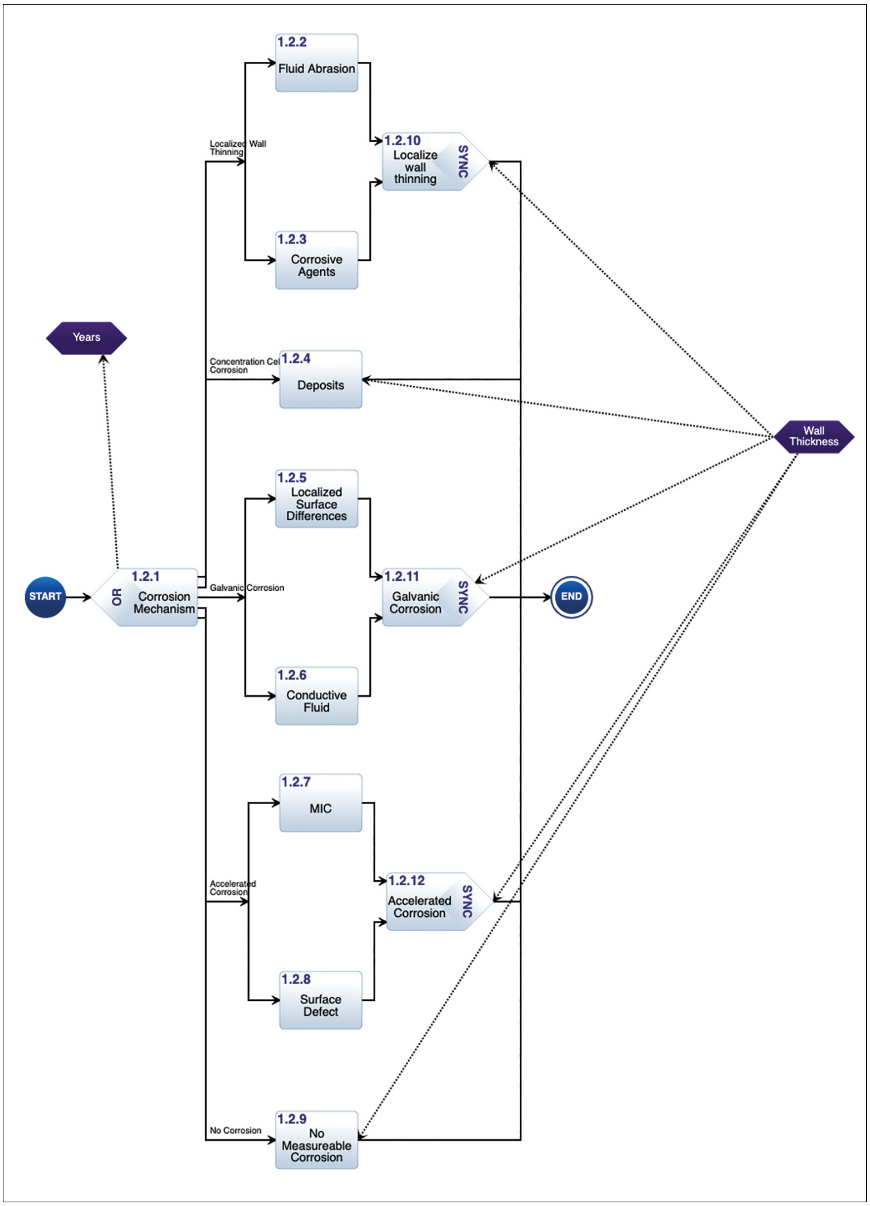

FIGURE 5. Innoslate Action Sub-diagram of Corrosion Mechanisms.

Case Study

This section presents a case study that uses the model to determine the effects of changing the inspection frequency and the plugging limit on the probability of a leak occurring between inspections within the service life of the condenser. The case study compares the nominal plugging at 70% wall loss with plugging at 60% wall loss. Another comparison is changing the nominal 6 year inspection interval to an 8 year inspection interval.

The source of the data for this case study are proprietary historical records. The plugging limits and inspection intervals were chosen to test the model and not related to any specific plugging limits or inspection intervals on Naval vessels.

The case study utilizes the relative probabilities shown in Table 2 in the Innoslate action diagram of Figure 4. In addition to the simplifications identified as part of the model, the case study assumes that the probability of detection is constant between 60% and 70% wall loss. The output from each run of the model includes the number of tubes expected to leak over the 50 year service life of the condenser and the number of tubes that were plugged. The number of tubes plugged is only used as a comparison value to quantify the impact of changing the plug state on the number of that will eventually need to be plugged.

The leak probability is shown with a 95% confidence interval which required the 5000 iteration Monte Carlo simulation to be run ten times for a total of thirty simulations. The results are shown in Table 3.

Discussion

The baseline case study values of a six-year inspection frequency and plugging at 70% correlate with the in-service data for the sample of Naval condensers. Comparing the baseline to the less frequent inspection frequency of eight years while holding the plug state constant results in an increase in the probability of a leak occurring between inspections. There is not a significant difference in the average number of tubes plugged in the model since this is related to the plug state. Decreasing the plug state to 60% while maintaining an inspection frequency of eight years reduces the probability of leak to about the same level as the baseline while the average plugged tubes doubles. This can be interpreted that lowering the plug state would result in double the amount of tubes plugged over the life of the condenser. These factors have to be weighed by a program office using risk informed in–service inspection to balance the cost of inspection, the impact of tube leak between inspections, and amount of heat transfer design margin in the condenser (i.e. number of tubes that can be plugged over the life of the condenser) (Vinod, Bidhar, Kushwaha, Verma, & Srividya, 2003).

Although these results are intuitive, the model provides a quantified comparison between different inspection frequencies and plug states. Current methods only adjust the inspection frequency and a qualitative comparison of the increased leak probability. The value of the model as demonstrated in the case study is the ability to quantitively compare changes to the inspection frequency and plug state to determine the risk of changing the status quo.

The model is dependent on tube material and wall thickness. Each material requires the determination of the corrosion modes that have the greatest effect on tube failure. Then the annual corrosion rates for each mode need to be determined as was done for copper-nickel in Table 1. The corrosion rates are the programmed into the model and are removed from the wall thickness resource as shown in Figure 5. The initial value of the wall thickness resource and the restoration of the wall thickness through plugging must be updated for the new wall thickness. The next step is to determine the probability of detection for the material under consideration as well as determining the relative probability between the corrosion modes. The relative probability between the corrosion modes requires verification for each application or condenser.

The model is general enough to be adapted to all shell and tube heat exchangers that are periodically inspected for flaws. Each different condition requires the knowledge of localized corrosion rates for the tubing and fluid combination. In addition, the simplification from the four state Markov model to a three state Markov model (Figure 3) requires that the identification of a flaw does not necessitate a change in the inspection frequency and that all the tubes are inspected at the defined interval.

The benefits of this approach are the ability to quantify the probability of leakage for different plug state and inspection intervals and that it lends itself to model complex processes and environments that are hard to quantify.

The limitations in this approach are that the user needs to have a knowledge of the corrosion modes impacting the tubing, the amount of time required to determine the relative probability between the corrosion modes, and the inability to predict tube plugging rates.

Future Work

There are a number of aspects of this model that require optimization. The first is the determination of the relative probabilities between the corrosion modes. The second is the localized corrosion rates for the various corrosion modes and third is the determination of the expected number of plugged tubes.

In this paper, the relative probabilities between the corrosion modes was determined by trial and error. An initial distribution was determined and then the model run to see how the output matched the available data. Changes to the relative probabilities were made until the model had good agreement with the data. There are solvers available that can automate this portion of the model development thus reducing the time define these parameters.

The localized corrosion rates were researched in literature and utilized in the model. The impact of these corrosion rates is also dependent on the relative probabilities of the corrosion modes, therefore a sensitivity analysis should be preformed to determine how critical these values are to the model. It may be determined that the number of simulated corrosion modes can be reduced or that setting corrosion rates within an order of magnitude is sufficient. This would allow the model to extend to similar materials without changing the corrosion rates and only adjusting the relative probability between the corrosion modes.

The determination of the expected number of plugged tubes was not the primary goal of the model and, therefore, not thoroughly investigated. The reported value was the average number of tubes plugged per iteration of the Monte Carlo simulation. The number of iterations was chosen as a nominal value. The number of iterations could be chosen as a multiple of the number of tubes in the condenser and the number of tubes plugged per iteration could be added and divided by the multiple of the tubes. The life of the condenser could be set to the age of the condenser at the last inspection and these values compared to in–service data.

The three optimizations discussed above could lead to: 1) a more accurate model with less iterative work, 2) a standard model for multiple tube types, and 3) further usefulness of the model in lifecycle planning for periodic maintenance.

Conclusion

This paper demonstrated the ability to use a three state Markov model with renewal process to create of model of a Naval condenser that is inspected with eddy current analysis at known inspection interval. In this paper, the renewal process is removing the tube from service rather than repair. This model allows the evaluation of the impacts of inspection frequency and the percentage of wall loss that represents the plug state to minimize life cycle costs associated with a leaking in-service tube and the periodic inspections. The results can be compared to the current in-service operating parameters to validate the model. Solutions were generated using the model-based systems engineering software Innoslate with action diagrams and Monte Carlo simulations. NEJ

AUTHOR BIOGRAPHIES

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