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(RESEARCH ARTICLE)

Condenser condition assessment in a thermal power plant: A comprehensive case study for performance optimization

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Abstract

The condition assessment of condensers in thermal power plants presents significant challenges, primarily due to the lack of comprehensive data, particularly in the context of non-destructive testing (NDT), which is often not collected consistently or systematically. This paper addresses these challenges by thoroughly reviewing available non-destructive test reports and microstructure analysis data to evaluate the health of the condenser in a 300MW thermal power plant. Key operational and performance parameters, such as back pressure, terminal temperature difference (TTD), temperature rise (TR), and chlorine content of colling water, have been analyzed to assess the condition of the condenser. Additionally, a degradation growth model is developed to predict tube failure, and a retubing strategy is proposed to mitigate the risk of failure and optimize performance.

Keywords: Condenser; Condition assessment; Non-destructive testing; Retubing; Degradation

1. Introduction

In thermal power plants, condensers play a critical role in maintaining operational efficiency by cooling the steam generated in the turbine and ensuring the smooth functioning of the Rankine cycle. The condenser's performance significantly impacts the plant's overall thermal efficiency and energy output. Over time, condensers experience wear and tear, leading to tube degradation, fouling, and scaling, which can eventually result in tube failures and a reduction in performance. Accurate assessment of condenser condition is essential for preventing unscheduled downtime, optimizing maintenance, and extending the lifespan of plant components.

Eddy current testing (ECT) has proven to be an effective technique for condition assessment across various industries, including power generation, oil and gas pipeline inspection, and the chemical industry. Recent advancements have enhanced both the quality and quantity of data obtained through ECT. Inspecting heat exchanger tubes to assess their operational status using eddy current testing is a time-consuming and labor-intensive process that requires the expertise of a skilled technician. Golovin et al. (2016) employed ECT to investigate localized corrosion in heat exchangers across different environments. ECT is particularly useful for detecting corrosion-related issues that render tubes unfit for service, especially in newly shipped stainless steel heat exchangers. According to Collier (1983), even a single failure in these large systems can result in significant financial losses. Lang et al. (2004) emphasized the high costs associated with tube failures, with commercial steam generator leaks potentially causing losses ranging from $2 to $10 million per leak, leading to major repairs that could last up to a week. The failure of heat exchangers in power plants can result in substantial production and capacity losses, particularly in fossil and nuclear power facilities.

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The importance of early detection of potential issues in condensers has been increasingly recognized, with various approaches being developed to monitor and assess their condition. While periodic inspections and visual assessments provide some insights, non-destructive testing methods such as ultrasonic testing, eddy current testing, and thermal imaging have emerged as valuable tools in diagnosing the condition of condenser tubes and detecting internal corrosion, erosion, and mechanical wear. These methods are, however, not always employed systematically, leading to gaps in data that hinder the accurate evaluation of condenser health.

This paper presents a case study that aims to address these challenges by reviewing non-destructive test reports and microstructure analysis data to assess the current condition of the condenser in a thermal power plant. By analyzing various operational and performance parameters, such as thermal performance, back pressure, temperature rise, and chlorine content, this study provides a comprehensive assessment of the condenser's health. Additionally, a degradation growth model is developed to predict tube failure over time, and a retubing strategy is proposed to mitigate potential risks and enhance the long-term efficiency of the condenser.

2. Condition Assessment Procedure

The condenser unit under consideration has been in operation since 1987, as a base load station in southern Michigan, USA. The capacity of this unit is approximately 290 MW with a pressure and temperature of 1950 psi and 1005^{o} F, respectively, at the superheater outlet. The unit, as well as the condenser, has been in operation for the last 37 years. A major rebuilds took place in 2013 and included partial retubing (top 5 rows) of the condenser. Since early 2024 the condenser has been experiencing a series of tube failures. In the 2024 calendar year to date 55 tubes were plugged in. So far 411 tubes have been plugged in. The condenser, as shown in Figure 1 has a total of 12,130 tubes which means approximately 3.40% tubes are plugged. Since August 10, 2024, when the last tube plugging was done, the sulphate concentration at the condensate extraction pump (CEP) discharge remains steady and there appears to be no further evidence at this time of any remaining tube leakage.

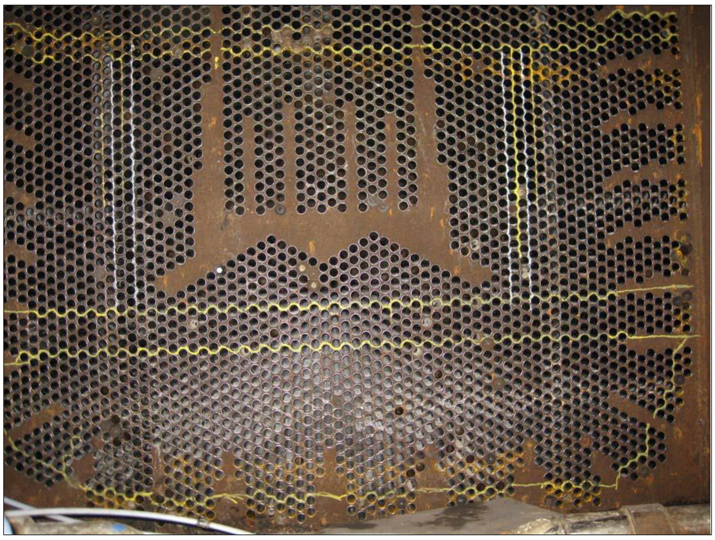

Figure 1 The lower quadrant of the condenser

In the last 15 years, only two NDE samples were done; one in 2012 and the most recent in 2020. Based on these two NDE test results, it is very difficult to get a tube degradation trend. Moreover, no visual inspection was performed on this condenser recently. According to EPRI guideline, NDE test result and visual inspection are required to perform condition assessment or remaining life assessment of the condenser (EPRI, *Ref: Proceedings: Condenser Technology Conference, GS 7349, 1991)*. Due to the lack of information, there was need for analysis of the unit historical data, industry experience and design data to determine the most likely damage mechanism.

2.1. Historical data analysis

The 2012 and 2020 NDE report was reviewed to determine their condition during the examination. A total of 54 of these tubes were inspected and had less than 20% wall loss as shown in Table 1.

Table 1 Comparison of plugged tubes with previous NDE test results

Condenser sections	**2012 NDE RESULTS (No. of tubes with 0-20% wall loss)**	**2020 NDE RESULTS (No. of tubes with 0-20% wall loss)**	**Latest tubesheet map, 2024**
Bottom West	18	4	Plugged
Bottom East	20	10	Plugged
Top West	8	4	Plugged
Top East	8	11	Plugged
Total	54	29	

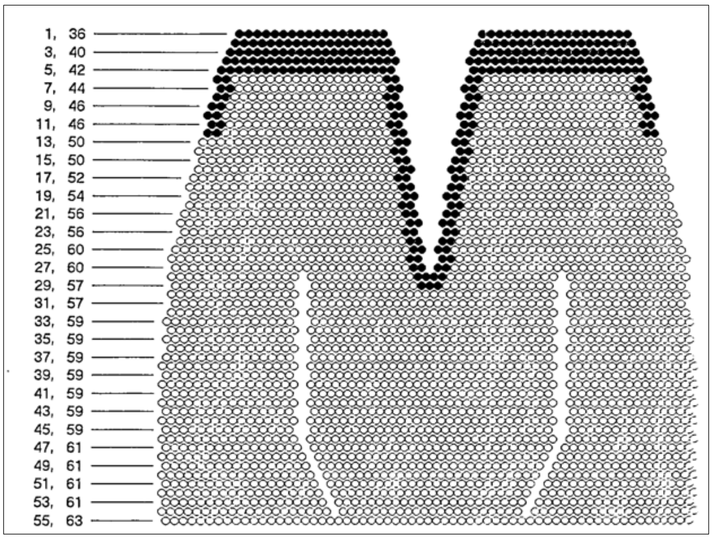

Figure 2 Condenser tubesheet map

The tubes previously tested as “good” (0-20% wall loss), which are now plugged as highlighted in the above comparison. Both 2012 and 2020 reports showed that these tubes were in “good” condition, which was 93.5% and 98.5% of the sample respectively. The defective tubes percentage was high in the 2012 test as compared to the 2020 test because the top five tube rows (severely affected area during 2012 test) were retubed in 2015 and most of the defective tubes were replaced. This table shows that in the last 14 years, 54 previously good tubes are now plugged in. In the last 5 years 29 previously good tubes are now plugged in. This demonstrates an increased rate of “good” tube degradation in the condenser condition from 2012 as the rate of “good” tube failures is increasing. This accelerated failure rate is typical for a condenser of this vintage. These plugged tubes are randomly distributed throughout the condenser, so the issue is not localized.

It should also be noted that there are 22 tubes from the 2012 NDE testing and 16 tubes from the 2020 NDE testing that were found with severe wall loss (>80%) that remain unplugged to date as shown in Table 2. The tube degradation appears random as good tubes are failing more quickly, and some severe wall loss tubes have not failed to date after 5-15 years. This is consistent with the pitting failure theory; however metallurgical testing is required to confirm the failure mechanism.

Table 2 Previous NDE report showing tubes with 81-100% wall loss, but not plugged in 2024

Condenser sections	2012 eddy current test data	2020 eddy current test data
Bottom west	12	5
Bottom east	6	7
Top west	4	4
Top east	0	0
Sub-total	22	16
Total: 38		

2.2. Historical Repair Analysis

It is worthwhile to mention that partial retubing of the condenser took place in 2015. Two past NDE report along with these retubing information were utilized to estimate remaining life and complete a condition assessment of the condenser at this stage. The repair history is shown in Table 3 and picture of plugged tubesheet is shown in Figure 3.

Table 3 Tube plugging history

Date	Description
October 2023	Plugged 32 tubes
November 20023	Plugged 24 East and 12 West tubes (36 total)
May 2024	Repair condenser leak (has hours, no record of number of tubes plugged)
June 2024	Plugged approx. 50 tubes between east/west side
July 2024	2 plugged top west, 2 plugged bottom east (4 total)
August 2024	3 tubes plugged in the top east section (3 total) (sulphate concentration significantly reduced to acceptable levels after this repair)

Figure 3 Plugged tubesheet face

According to the 2020 NDE report, approximately 30% tubes were tested and most of the tubes were reported to have OD wall loss. As wall loss was external, the most likely cause of the loss was from steam erosion. However, if we consider the latest NDE report summarized below, it clearly shows that most of the tubes have ID wall loss. Most likely cause of the ID wall loss is from pitting. Pitting erosion is accelerated significantly in the presence of MIC microbiological induced corrosion (MIC). The 2020 Eddy current test results are summarized below.

Table 4 2020 Eddy Current Test Result

	Top east section	**Top west section**	**Bottom east section**	**Bottom west section**	**Cumulative**
Total tube	3034	3034	3031	3031	12130
Tubes tested	604	584	627	465	2280
Percentage of tube tested	19%				
Wall loss indicated					
ID >80%	0	3	3	5	11
61-80%	0	1	0	6	7
41-60%	0	2	0	1	3
21-40%	0	3	1	1	5
11-20%	0	0	0	0	0
Total	0	9	4	13	26
OD >80%	0	1	1	3	5
61-80%	0	0	0	0	0
41-60%	0	1	0	3	4
21-40%	0	0	0	0	0
11-20%	0	0	0	0	0
Total	0	2	1	6	9
Total tubes with wall loss	0	11	5	19	35

Approximately 20% of the tubes were tested in 2020. If a projection of failed tubes is created based on the results to 100% of the tubes (12,130 tubes in condenser), then we can expect roughly 1.3% of the tubes have been plugged between 2012 and now (40% to >80% wall loss). This indicates that roughly 158 tubes should require plugging or be plugged already. According to maintenance records approximately 123 tubes were plugged in from 2021 to August 2024. This is close to the estimated number of projected plugged tubes 158.

2.3. 2024 Condenser Repair Analysis

In 2024, the condenser experienced outages in April, June, July and August. In April the sulphate concentration was noted to be outside of the recommended parameters and remained at concerning levels until after the August repair. This series of outages in 2024 certainly appears to be concerning however, this was in part due to the original issue creating these unacceptable sulphate levels remaining unaddressed. The challenge in locating this leak was likely due to the location of the tubes plugged (3) being in the top left corner. The repair was conducted using mechanical seal plugs as proposed by Wolf and Adams (1995). The mechanical plugs have improved gripping and sealing capability specifically aimed at successful operation under the severe operating conditions found in high-pressure heat exchangers. For the weld repair, the potential for fatigue failure, differential thermal expansions, stress corrosion cracking (SSC) is high as indicated by Liu et al. (2016), Huang et al. (2018), Wei and Ling (2015), Guo et al. (2011), Corleto and Argade (2017). Therefore, to have a reliable weld joint, the technique provided by Huang et al. (2018) and Rahman (2024b) was applied. Before returning the condenser to service, a series of pressure and dye penetrant tests were conducted to confirm the integrity of the repair and ensure leak-tightness.

Filling the condenser above this level can be difficult and is challenging due to the lack of hydrostatic pressure at this point to indicate a leak is present. For leaks at this level a foam machine is more effective to detect leaks on the top row(s). In August a foam generator was used to detect leaks, and the repairs were very successful. Sulphate levels were well under recommended limits in August repair to when this investigation was completed. Foam generator is a very useful tool for leak detection and very cost efficient. Farrahi et al. (2019) discussed the challenges associated with repairing deep cracks in tube-to-tubesheet welding, which may necessitate the removal of affected tubes from service.

2.4. Chloride Concentrations in Cooling Water

The EPRI proceedings with similar tube/tube sheet materials in their condensers with tube material: A304-A249 & Tube sheet: A285C were reviewed to get insight of similar experience by other utilities. The EPRI proceedings studied were:

- Failure Cause Analysis- Condenser and Associated System, Volume 1, EPRI, CS-2378, 1982.
- Proceedings: Condenser Technology Conference, EPRI, GS-7349, 1991.
- Corrosion-Related Failures in Power Plant Condensers, EPRI, NP-1468, 1980

According to EPRI (*Ref: Failure Cause Analysis- Condenser and Associated System, Volume 1 EPRI, CS-2378, 1982*) type A304 stainless steel is excellent for freshwater service and can be expected to last 30 years or more. This material should be employed in cooling waters with less than 70 ppm chlorides to minimize water side pitting. However, chloride content in the plant varies all over the year and it is tested sporadically.

It is evident that chloride content in cooling water varies from as high as 473 ppm (Feb 12, 2024) to as low as 17 ppm (August 18, 2024). The plant has been running for the last 37 years and cooling water chloride ppm levels vary above the recommended limit periodically. Since this water comes from the reservoir, the chloride levels vary naturally throughout the year. That is why cooling water chloride ppm is not possible to maintain all the time according to EPRI recommendation.

2.5. Metallurgical Test

Metallurgical tests on the sample condenser tubes were last performed in the year 2021. Three tube samples were pulled out from the condenser for metallurgical assessment. Pitting and steam side erosion are the major failure modes for stainless steels in condenser applications. Pitting in chloride-containing environments results in frequent failures of stainless steel (*Ref: Corrosion-Related Failures in Power Plant Condensers, EPRI, NP-1468, 1980*). The latest eddy current test data indicates that most of the wall losses are related to the ID wall loss which may be an indication of pitting erosion. In addition, MIC may initiate or accelerate the pitting corrosion. As MIC was detected in the tubes in past, it is likely that pitting as well as deposition of microorganisms may cause recent tube failures.

2.6. Thermodynamic Analysis

A total of 411 tubes have been plugged and the percentage of plugged tubes is 3.40%. The percentage of plugged tubes is still low according to the normal industry practice for condenser end of life (10% of total tubes or 1213 tubes in this case). There is no evidence of deteriorating performance of the condenser. Cooling water outlet temperature is at or near design condition throughout the year during full load. Other than a couple of hot weeks in summer where seasonal derates occasionally occur, this condenser runs well with no sign of performance degradation.

The condensing of the steam requires the condenser to remove the heat of vaporization from the steam and reject it into the cooling water. The cooling water outlet temperature should be as close as possible to the saturation temperature of the exhaust steam at condenser pressure to successfully remove the energy from the turbine exhaust steam to condense it (*not below 5 ° F, according to the Heat Exchanger* Institute *(HEI), Sec 4.1.2 Standards for Steam Surface Condensers, HEI, ninth edition*). The Temperature Rise (TR = circulating water outlet temperature – circulating water inlet temperature) as well as Terminal Temperature Difference (TTD = saturation temperature of exhaust steam – circulating water outlet temperature) are two vital parameters to estimate effectiveness of the condenser. In Table 5 below, several online data are compared with the design data of the condenser.

Table 5 Comparison between design temperature data with online

Date	Load (MW)	CW Inlet Temp (°F), T1	CW Outlet Temp (°F), T2	Back Pressure (in of Hg abs.)	Saturation Temperature (°F), Ts	TR (T2-T1)	TTD (TS-T2)
Design	300	70	98	3.0	115.1	28	17.1
7/10/2024	293	80.9	116.0	4.66	131.1	35.1	15.1
7/15/2024	300	80.3	111.8	4.17	127.0	31.5	15.2
7/17/2024	299	82.7	109.8	4.15	126.8	27.1	17
7/20/2024	300	82.1	110.8	4.06	125.9	28.7	15.1
8/17/2024	294	84.2	113.5	4.21	127.3	29.3	13.8
8/18/2024	299	82.4	114.0	4.40	128.9	31.6	14.9

During some summer days, hot cooling water inlet temperature requires to derate the unit according to the performance curve of the condenser. Other than these few days, this condenser has no problem throughout the year. This condenser is designed for 28° F cooling water Temperature Rise (TR = circulating water outlet temperature – circulating water inlet temperature). The data was obtained from PI for 2024 July and August when cooling water inlet temperature higher than 80° F and it is observed that CW temperature rise is very close to 28° F most of the time. This means that the cooling water is taking enough heat away from the condenser and thermally the condenser is performing well even in the hot summer days.

Several hot summer days are chosen to represent the data in above mentioned table. During these extreme hot days (CW inlet temp more than 80° F) the TTD is below the design condition and at the same time TR values also show close to the design value or even higher. The design temperature range for this condenser is 70-85° F and in 2024 CW inlet temperature is not recorded more than 84.2°F. Approximately 4.5 in of Hg abs and or more than 85° F circulating water inlet temperature will cause derate for the unit. Even in the hot summer days, this condenser performs well from a thermodynamic point of view with all these plugged tubes. Thermal performance and back pressure of the condenser is estimated by theoretical design calculations for three different conditions and listed in the following Table 6:

- Condition 1: Condenser current operating condition - 70°F circulating water inlet temperature with 411 plugged tubes
- Condition 2: Operating condition in summer months - 85°F circulating water inlet temperature with 411 plugged tubes
- Condition 3: Operating conditions in summer months - 85°F circulating water inlet temperature with 10% increase in total number of condenser tubes and 1000 GPM increase in flow rate from design

Table 6 Thermal performance analysis of condenser under different scenarios

Condition	Circulating Water Inlet Temp. T_1 (°F)	No. of Tubes	Saturation Temp, T_s (°F)	Saturation Pressure, P_s (in Hg. abs)
Design	70	12126	115.10	3.01
Condition 1	70	11715	115.56	3.05
Condition 2	85	11715	129.26	4.44
Condition 3	85	13339	127.34	4.22

Condition 1 shows the back pressure due to the reduced number of tubes due to plugged tubes (411 tubes). There is negligible deviation from design back pressure for this condition. It indicates that there is no deteriorated thermal/heat transfer performance for the plugged tubes. Condition 2 shows back pressure for cooling water inlet temperature as high as 85° F. It results in higher back pressure than design condition, but the unit still does not require a derate (up to 4.5 in of Hg abs. unit doesn't require derate). Condition 3 shows the back pressure with 10% more tubes and cooling water inlet temperature at 85° F. High cooling water inlet temperature related derates during summer days could be addressed by adding more tubes in the condenser. It can be theoretically possible to reduce the back pressure (From 4.44 in of Hg to 4.22 in of Hg, comparing Condition 2 & 3). Economically Condition 3 may not be a good solution, as it requires redesigning the whole condenser.

During hot summer days, some derates are expected (if temperature exceeds 85° F) but the rest of the year this condenser operates properly. From Table 6, it can be predicted that thermal performance has not deteriorated yet due to the plugged tubes.

Based on the above-mentioned thermal analysis it is reasonable to conclude that this condenser performs according to the design condition even in the hot summer months having reduced tubes from plugging. The deficiency was only apparent when lake temperatures were high between May and October, when high back pressures limit unit output. It is worthwhile to mention here that the main limiting factor was the exhaust back pressure on the low-pressure section of turbine, denoted as L-0 turbine blades that caused derates during hot summer days. A new design, closed cover band (CCB) was installed during low pressure cylinder replacement in 2020. The CCB blades have a higher design backpressure rating than existing blades.

2.7. Projected Useful Life

To assess the condition of the tubes and project their degradation over time, two consecutive eddy current test results showing the percentage of tube wall loss were compared, as introduced by Rahman (2024 (a)). However, it is essential that the variables of the eddy current examination (such as operating frequencies, eddy current probe, eddy current system, extension cables, etc.) remain constant between outages. The recent accelerated tube failure indicates rapid degradation of the tubes, which may not be accurately projected by the linear model. This is evident from the lower R-squared value of 0.6788. In addition, it is unclear whether these variables were kept constant for the condensers. Given these factors, the original linear degradation model proposed by Rahman (2024 (a)) was extended to power and polynomial tube wall degradation growth models. These extensions resulted in a higher R-squared value, indicating a stronger fit as illustrated in Figure 4.

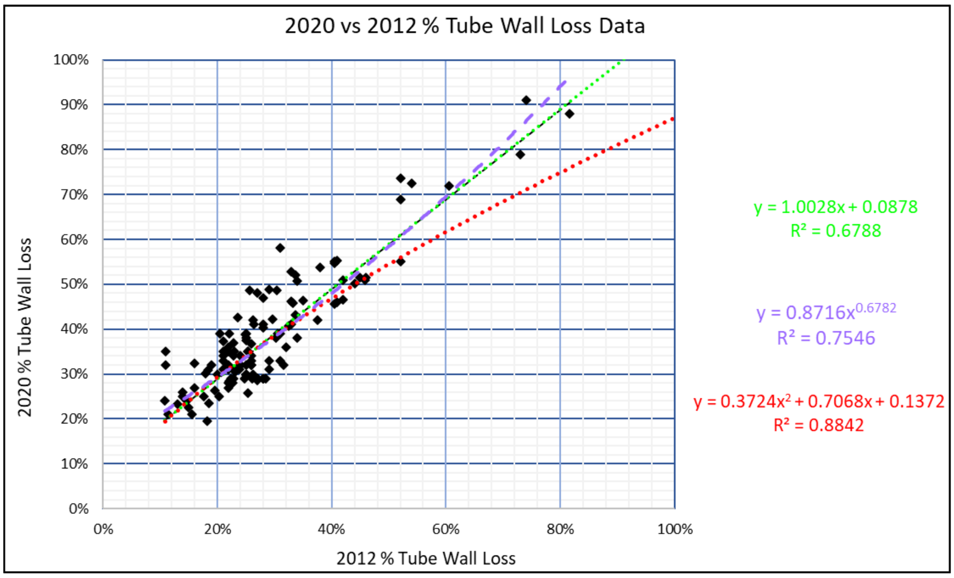

Figure 4 Projection of tube wall loss using two consecutive eddy current test data

The power degradation growth model has higher R-squared value compared to polynomial model and therefore used in the current analysis. Using the projected wall loss, it is estimated that out of 12,130 condenser tubes, approximately 960 tubes will approach 60% wall loss by 2027, including those that are already plugged. This represents about 8% of the total tubes, which could significantly impact the condenser's ability to remove heat from the system.

3. Future Recommendations and Refurbishment Plans

- To predict the remaining life of the tubes, NDE should be performed on approximately 40% of the tubes (Sec 4.1.2.2, Guideline for Condition Assessment and Inspection of Fossil Plant Heat Exchangers, EPRI, 1006305,

2001) during next minor overhaul. According to EPRI the final percentage varies from component to component and plant to plant, but it is typically in the range of 15% to 30%; the sample scheme of 40% was found to be nearly as effective as 100% inspection for detecting and repairing defective tubes. It is recommended

- At the same time a few plugged tubes (at least four) need to be pulled and metallurgically tested for failure analysis.
- Before finalizing any retubing decision, failure analysis of plugged tubes as well as eddy current test and visual inspection are necessary to predict the trend and remaining life of the tubes/tubesheet accurately. Equipment Integrity will update this condition assessment report after additional data is collected in 2016 outage.
- Based on EPRI recommendations (*Ref: Failure Cause Analysis- Condenser and Associated Systems, EPRI, CS-2378, 1982*) and tube leakage trends, it is not unrealistic to believe that these tubes are seeing end of life and a retubing project can be initiated in near future based on the test data and failure analysis. Webb (2011) conducted a similar analysis using two enhanced condenser tubes in a nuclear plant and found that the increased cost of enhanced tubes can be quickly recovered through improved heat rate and increased generation capacity. A few options for retubing are listed in Table 7.
  - Option 1 partial retubing - Possibly partial retubing can be done but it will not provide 100% remedy of the outage/derate due to condenser tube failure.
  - Option 2 full retubing - Full retubing is possibly the right approach and this will only ensure the 100% elimination condenser tube failure
  - Option 3 full tube replacement with advanced alloy steel material - may not be feasible as this unit is currently planned to retire in 2027 (unless a major rebuild of the entire unit is approved)

Table 7 Cost Estimation for Retubing

	Option 1 **Full retubing**	**Option 2** **Partial retubing (50%)**	**Option 3** **Full retubing (including tubesheet) with alloy steel**
Duration	40 days	21 days	50 days
Labor	1.9 million	1.3 million	2.2 million
Material	0.7 million	0.4 million	1.5 million
Contingency	1.1 million	0.6 million	1.0 million
Total	3.7 million	2.3 million	4.7 million

A cost estimate for different options for retubing is listed in the above table. Any full retubing option needs a major outage but partial retubing can be done in a minor outage. That is why Options 1 & 3 are not realistically possible before 2020 without taking an extended outage not currently in the maintenance schedule, and Option 2 can possibly be executed as early as the 2018 minor overhaul

4. Conclusion

The condenser tubes in the unit have been in service for nearly 37 years and have experienced issues related to water quality and acid cleaning in the past, although these practices are no longer followed. Given their age and history, the need for retubing before 2027 is a distinct possibility. However, a more accurate prediction regarding the necessity and timing of retubing will be made following the reassessment of the condenser in 2026. This reassessment, which will include eddy current and metallurgical testing, will provide critical data to inform decisions regarding capital investments and the potential initiation of a retubing project.

Four potential options for retubing have been outlined in this report. The option involves full retubing with the existing A304 material, while the alternative proposes the use of a more durable alloy steel for full retubing. Both options require major outages. The alternative offers a partial retubing approach, which would require a minor overhaul. Given that the unit is slated for retirement in 2027, a full replacement with advanced alloy may not present a cost-effective solution.

Compliance with ethical standards

Disclosure of conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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