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Reducing Subjectivity in Inspection Decisions using Extreme Value Analysis

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Abstract - **Inspecting tubes in shell-and-tube heat exchangers is a major activity in many refineries, chemical, fertilizer, and petrochemical plants. Non-destructive methods, including Eddy Current Testing, Internal Rotary Inspection System Testing, and Saturated Eddy Current Testing, are performed to assess the condition of tubes. The existing condition of tubes is used to estimate their suitability for continued operation till the next inspection or maintenance opportunity, typically the next turnaround.**

In this organization, initial selection of tubes for testing is based on Appendix 312-I of PCC-2 from the American Society of Mechanical Engineers (ASME). The current condition of the tubes in the tube bundle was assessed based on test results. The need for further testing was then decided. In deciding so, PCC-2 was not referred by this organization. Engineers differed in their decisions regarding the need for and extent of further testing.

To minimize subjectivity in inspection decision-making, Extreme Value Analysis (EVA) was used. This is a case study about the usage of EVA in inspection decision-making. This work proposes a practical decision-making framework using EVA.

Keywords: Tubes in Shell and Tube heat exchanger; Tube condition assessment; Extent of examination of tube bundle; Extreme Value Analysis; Subjectivity; Decision making; Microsoft Excel

I.INTRODUCTION

Shell-and-Tube (S&T) heat exchangers are among the most commonly used types of equipment in process industries, including refineries, petrochemical, fertilizer, and chemical plants. They facilitate heat transfer between two fluids without direct contact between the fluids. During operation, these heat exchangers are susceptible to deterioration due to the nature of the operating fluids, operating conditions, and other factors. Such deterioration may manifest in the form of localized corrosion, generalized corrosion, or other forms of degradation.

S&T heat exchangers are typically opened for cleaning during scheduled maintenance, changeovers, breakdowns, and plant turnarounds. During breakdowns and turnarounds, the condition of the tubes is assessed using non-destructive examination (NDE) techniques such as Eddy Current Testing (ECT), Internal Rotary Inspection System (IRIS) Testing, and Saturated Eddy Current Testing (SECT), among others. These examinations provide measurements of tube wall thickness, which form the basis for assessing the current condition of the tubes, determining their rate of deterioration, and evaluating their suitability for continued service until the next planned inspection or shutdown.

Tubes that are predicted to reach or exceed their allowable deterioration limits before the next inspection opportunity are either plugged or replaced. Thus, the assessment of tube thickness and its deterioration rate is critical to ensure the mechanical integrity, reliability, and safe operation of S&T heat exchangers.

In many organizations, the extent of tubes inspected by NDE is only a fraction of the total number of tubes present in a tube bundle. For organizations following the PCC-2, general recommendations and requirements for determining the minimum number of tubes to inspect are given in Mandatory Appendix 312-I, and the tubes are inspected accordingly. A decision on inspection of a greater number of tubes is based on these readings. If further inspection is not based on PCC-2, other factors considered include, but are not limited to, the characteristics of the fluids on both the shell and tube sides, service life of the tubes, tube material, history of the exchanger, operational upsets experienced during operation and before stoppage.

Based on the evaluation of these tubes, recommendations like process parameters monitoring, exchanger maintenance, operational practices, and future actions such as tube procurement for retubing the tube bundle at the next opportunity are made.

Reduction of tube wall thickness may not be uniform and is more likely to be localized, such as pitting, erosion. In a tube bundle with many tubes, tube bundle failure occurs at the most degraded point. One way to identify the most degraded tube is to examine all the tubes, which is expensive and requires extended downtimes. This can be avoided by employing a statistical method called Extreme Value Analysis (EVA). EVA aims to identify the weakest rather than standard averages. Wall thickness loss measurements from representative tubes can be used to estimate the extreme thickness loss in untested tubes within the tube bundle using

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EVA. Using EVA avoids unnecessary tube replacements and prevents unplanned outages due to leaks, thus optimizing both maintenance schedules and operational safety.

II. INTRODUCTION TO EVA

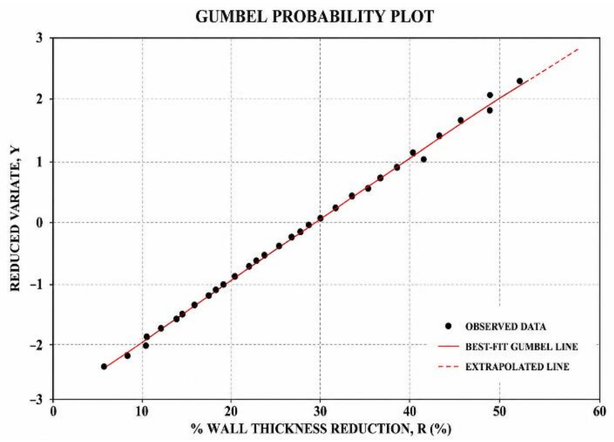

Fig. 1: A Gumbel probability plot

EVA is a statistical method used to model and assess the probability and magnitude of rare, extreme events that may have significant or severe consequences. In this case study, the EVA methodology is based on the American Society for Testing and Materials (ASTM) standard ASTM E2283-08(2019). The standard considers the Gumbel extreme value distribution. For this distribution, the probability density function is given by

$$f(x) = \frac{1}{\delta}[\exp(-y)] \, . \exp[-\exp(-y)] \quad (1)$$

And the cumulative distribution function is given by

$$F(x) = \exp(-\exp(-y)) \quad (2)$$

$$\text{Where, } y = (x-\lambda)/\delta \quad (3)$$

- λ is the location parameter of the extreme value distribution function
- δ is the scale parameter of the extreme value distribution function
- x is the maximum wall loss

x_i is the maximum wall loss in each tube,
where $1 \le i \le n$, where n is the number of tubes sampled

Acceptability of usage of EVA is given in Mandatory Appendix 312-I, ASME PCC-2. The confidence intervals that give appropriate inspection effectiveness are 99%, 95%, 90%, and 80%, when lower-bound values are considered.

Inspection engineers do not use EVA widely for various reasons, including:

- Lack of awareness
- Non-acceptance of statistical methods by management
- Inexpensive NDE
- Availability of time for inspection
- Equipment has a history of failure
- Relying on inspections instead of relying on estimates, as a breakdown is not affordable
- Complexity of evaluation
- Blame culture in organizations
- Any combination of the above reasons

III. EXISTING PRACTICE

The organization under study is a refinery. The results of inspection of the tubes are used in assessing the integrity of the tube bundle. The practice followed by this organization is to conduct initial inspection of a minimum number of tubes following the recommendations of PCC-2. The further inspection scope was not always in accordance with PCC-2.

When tube thickness measurements were reviewed by two different inspection engineers, different decisions regarding the need to inspect the tube bundle further resulted. The basis for the recommendation to broaden the inspection scope of tubes was subjective. The two engineers considered the following ten points in recommending or not recommending further inspection – history of the equipment, service life of the tubes, corrosive nature of the fluids handled, next available maintenance opportunity, extent of degradation, consequence of failure, nature of corrosion, suitability of material of construction of tubes to operating conditions and fluids, operational upsets, and availability of spare tubes. To reduce this subjectivity and facilitate better decision-making, EVA was used. So, this paper outlines the methodology utilized to minimize this subjectivity.

The existing practice in the organization was inspecting the tubes, followed by evaluation of the condition of tubes based on the measurements made. Short-term (ST) and Long-term (LT) corrosion rate (CR) were calculated. The remaining life (RL) was evaluated using the formula:

$$RL = \frac{T_{current} - T_{min}}{CR} \quad (4)$$

Where $T_{current}$ is the current actual tube wall thickness, T_{min} is the minimum required wall thickness for design conditions, and CR is the corrosion rate. RL is calculated for both LTCR and STCR. The lower RL was chosen and compared against the time till next turnaround / suitable maintenance opportunity.

Any tube(s) that fell short of the above criteria was/were plugged, and the exchanger was released for further testing or for operation. The process is represented as a flow-chart in Figure 2.

The organization did not have an established practice of using statistical analysis to support inspection decision-making. Decisions were made only after actual inspection. Whether to conduct an actual inspection or not was decided by engineers based on the ten points mentioned above.

IV. METHODOLOGY

The degree of subjectivity in inspection decision-making between the two engineers was quantified using the percentage disagreement method. Data on tube wall thickness loss were obtained and then analyzed statistically using EVA, and then a decision on the further inspection requirement was made. Modified Anderson-Darling test was used to check the goodness of fit. The extreme values for tube wall thickness loss were estimated in the uninspected tubes. Based on this estimation, the decision was made to conduct a partial inspection or a total inspection of all tubes in the tube bundle.

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The above methodology was used to analyze three exchangers. Representative sample tubes, to include all the areas of the exchanger, were taken, and tube wall thickness loss readings associated with these tubes were taken as the sample data set for EVA. Tubes from the interior sections were selected. The tubes on the periphery, at the inlet nozzle, outlet nozzle, and pass partition were not considered, as they can have a different damage mechanism or corrosion rate from that of the other tubes.

The ideal sample size for EVA is 20 – 30 tubes, regardless of the number of tubes in the heat exchanger [1]. So, 30 sample tubes were chosen for two exchangers and 28 tubes for the third exchanger. Confidence intervals (CI) considered for this analysis were 99%, 95%, 90%, and 80%.

Microsoft Excel program was used for all calculations.

V. SUBJECTIVITY

The three exchanger units and the ten variables were considered for evaluating the percentage disagreement between the two engineers in inspection decision-making. 47% was the existing percentage disagreement.

VI. EVALUATION USING EVA

Exchanger 1: This exchanger has SA179 tubes with a nominal wall thickness of 2.11mm and an outer diameter of 19.05mm. The tubes had a service life of 5 years. Tube inspection was conducted using SECT. Based on the measured tube thickness values, the RL of the tube bundle was calculated and compared with the time to the next turnaround. The thickness reduction for which RL $\leq$ time to next turnaround was evaluated. This value was >25% tube wall thickness reduction, and all such tubes were to be plugged as per the organization's existing practice.

The total number of tubes (including interior tubes inspected as per PCC-2 recommendations) was 1256. Within this, 30 representative tubes from the interior were selected, and their wall thickness loss was used for estimating the wall thickness loss in other interior tubes, using EVA. A modified Anderson-Darling statistic was evaluated to check the goodness of fit, and the value was found to be 0.7179. Hence, at the 5% significance level, there is insufficient evidence to reject the null hypothesis (the null hypothesis is that the data follow a Gumbel distribution). Thus, the data followed a Gumbel distribution.

A range of % thickness loss values for the 99%, 95%, 90%, and 80% CI were generated and shown in Table I.

TABLE I. CI VS. RANGE OF WALL THICKNESS REDUCTION

CI	Range % (min – max)
99%	28 – 47
95%	30 – 45
90%	31 - 44
80%	33 - 42

The probability of finding at least one tube in the remaining tubes that exceeds 25% tube wall thickness reduction is evaluated as100%. The results of the EVA estimated 44 tubes to meet the plugging criterion. Based on the above results, both engineers recommended inspecting the remaining tubes.

During subsequent tube thickness measurement, a total of 41 tubes were found to meet the plugging criterion. This gave a 7.3% error in the estimation of the number of tubes that met the plugging criterion. The highest thickness reduction found after complete inspection was 46%.

Exchanger 2: This exchanger has SA179 tubes with a nominal wall thickness of 2.11mm and an outer diameter of 19.05mm. The tubes had a service life of 5 years. The total number of tubes (including interior tubes inspected as per PCC-2 recommendations) is 1256. From these, 30 representative interior tubes were selected, and the wall-thickness loss measured in these tubes was used to estimate the wall-thickness loss in the remaining interior tubes. Tubes with a thickness reduction of >27% were to be plugged in accordance with the existing practice.

SECT was conducted. The modified Anderson-Darling statistic was 0.6833. Hence, at the 5% significance level, there is insufficient evidence to reject the null hypothesis (the null hypothesis is that the data follow a Gumbel distribution). Thus, the data followed a Gumbel distribution. Table II shows CI vs range of % thickness loss values.

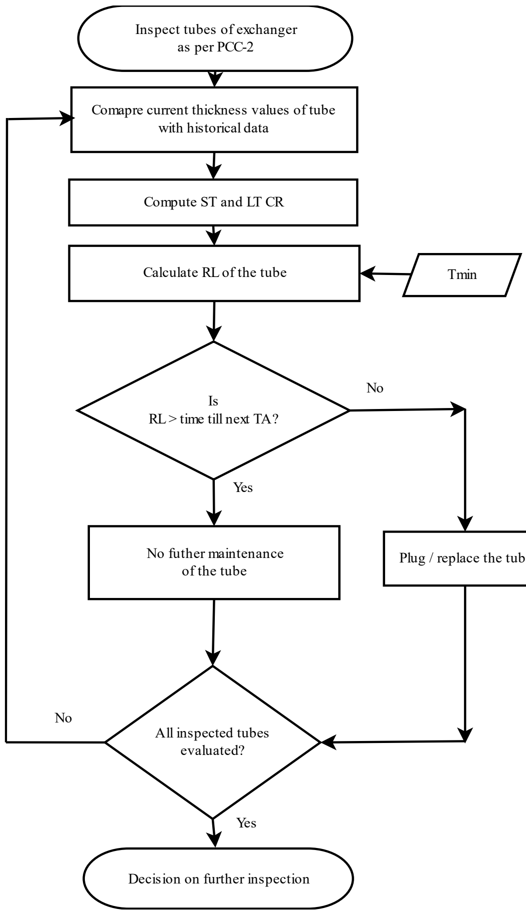

Fig. 2: Existing practice

TABLE II. CI VS. RANGE OF WALL THICKNESS REDUCTION

CI	Range % (min – max)
99%	29 – 50
95%	32 – 47
90%	33 – 46

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80%	35 – 44

The probability that at least one tube meets the plugging criterion in the uninspected tubes is evaluated as 100%. Based on the above results, both engineers recommended inspecting the remaining tubes. The number of tubes with a thickness reduction of >27% was 44, while the estimated number of tubes meeting the plugging criterion was 39. This is a 12.8% error in estimation of the number of tubes that met the plugging criteria. The highest thickness reduction found after complete inspection was 42%.

Exchanger 3: This exchanger has SA214 tubes, with a nominal wall thickness of 2.11mm and an outer diameter of 25.4 mm. The tubes had a service life of 8 years. The total number of tubes (including interior tubes inspected as per PCC-2 recommendations) was 574. Within this, 28 tubes from the interior were selected, and their wall thickness loss was used to estimate the wall thickness loss in other interior tubes.

SECT was conducted on 28 tubes out of these 574 tubes. Tube plugging was to be conducted for a tube wall thickness loss >26%. The probability that at least one tube exceeds 26% tube wall thickness loss in the remaining tubes is evaluated as 99.999%.

The modified Anderson-Darling statistic was 2.2583, above the critical value at the 5% significance level. The data therefore did not fit a Gumbel distribution. Despite the poor fit, engineers recommended inspecting the remaining tubes.

Based on the EVA, 12 tubes were expected to exceed the 26% plugging threshold. Upon full inspection, 102 tubes were found above 26%. This is an 88.2% error. The highest thickness reduction found was 64%.

This case shows why goodness-of-fit needed to be checked before trusting an EVA estimate. The failed Modified Anderson-Darling test tells us the Gumbel distribution didn't fit this tube bundle's data. A simpler explanation is that this bundle's corrosion pattern produced a heavier-tailed distribution than Gumbel allows, which would explain why the estimate came in so far below the actual count. Multiple corrosion mechanisms are also possible. Given the scale of degradation found, this bundle was recommended for retubing, along with an investigation into the cause.

Table III shows CI vs range of % thickness loss values.

TABLE III. CI VS. RANGE OF WALL THICKNESS REDUCTION

CI	Range % (min – max)
99%	25 – 51
95%	28 – 47
90%	30 – 46
80%	32 - 44

VII. PROPOSED METHODOLOGY

While EVA offers several other potential applications, this case study focuses on its use in reducing subjectivity in inspection decision-making. The proposed methodology incorporating the usage of EVA is given in Figure 3.

VIII. DISCUSSION

- The primary purpose of this statistical evaluation is to reduce subjectivity in inspection decision-making for heat exchanger tubes
- The percentage disagreement between the two engineers was quantified at 47%. After basing the recommendation to further inspect all the tubes on EVA, the percentage disagreement reduced to 17%, with the disagreement limited to the nature of corrosion
- Conducting the analysis helped identify degraded tubes that would otherwise have gone undetected, thus reducing the risk of unplanned failures
- The accuracy of the number of tubes estimated to have a wall loss above the limit is reasonable when a good fit of the data is present. A good fit (Exchangers 1 and 2) gave mildly conservative estimates, while a poor fit (Exchanger 3) led to significant under-prediction and insufficient maintenance planning
- This analysis estimates thickness reduction in heat exchanger tubes, aiding in optimizing inspection activity, reducing costs, and saving time during maintenance turnarounds

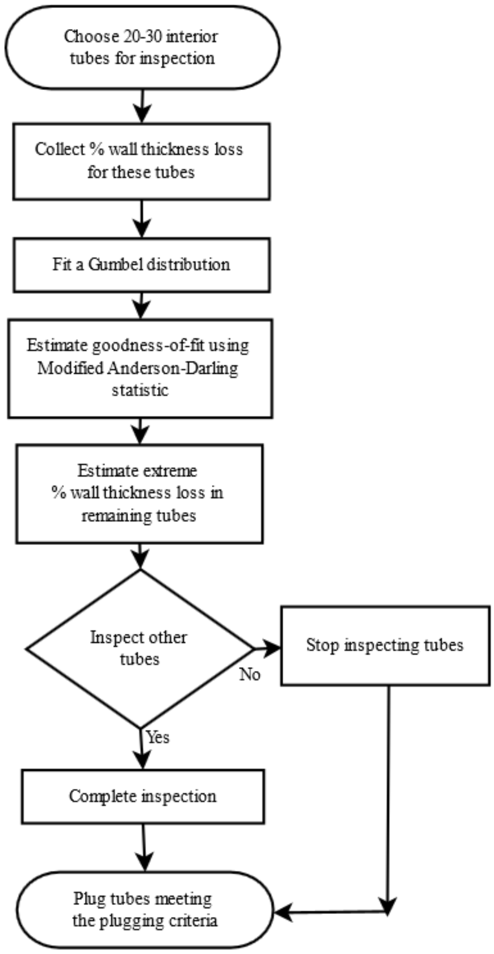

Fig. 3: Proposed methodology

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IX. CONCLUSION

This case study demonstrates the use of EVA as a practical tool for reducing subjectivity in deciding whether to extend inspection of S&T heat exchanger tube bundles beyond the minimum scope recommended in ASME PCC-2. By fitting a Gumbel distribution to % wall-thickness-loss measurements from a representative sample of tubes, EVA allowed the number of tubes likely to exceed the plugging criterion to be estimated before committing to a full inspection, replacing individual engineering judgment with a reproducible statistical estimate.

The three case studies show both the value and the limits of this approach. Where the Gumbel distribution fit the sampled data well (Exchangers 1 and 2), the EVA-based estimate of the number of tubes exceeding the plugging threshold was reasonably close to the number found on complete inspection, with errors of 7.3% and 12.8% respectively. Where the goodness-of-fit test failed (Exchanger 3), the estimate was off by 88.2%, and the highest wall loss found (64%) exceeded even the most conservative 99% confidence bound predicted by the model. An EVA estimate is only as trustworthy as the fit of the assumed distribution to the data and goodness-of-fit verification.

Accordingly, EVA should be used as a decision-support tool alongside standard NDE and good engineering judgment. When goodness-of-fit is confirmed, EVA offers a defensible, quantitative basis for deciding whether to extend inspection scope. When goodness-of-fit is poor, as in Exchanger 3, this itself is informative: it signals that the tube bundle's degradation may not be adequately described by a single homogeneous process, warranting full inspection and a root-cause investigation rather than acceptance of the statistical estimate.

Overall, integrating EVA gives refineries and similar process plants a structured, repeatable framework for turnaround inspection planning - reducing reliance on individual engineering opinion while still requiring engineering judgment to interpret goodness-of-fit results.

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