

INSPECTION OF TUBULAR HEAT EXCHANGER BUNDLES: A STATISTICAL APPROACH

Ricardo Schayer Sabino, schayer@petrobras.com.br

Paulo Pio Alvisi, paulopa@petrobras.com.br

Helder de Souza Werneck, heldersw@petrobras.com.br

Petrobras – UN-REGAP – Rod. Fernão Dias BR 381, km 427, Betim – MG. CEP 323530-000

Carlos Alberto Cimini Jr., carlos.cimini@gmail.com

Universidade Federal de Minas Gerais – Av. Antônio Carlos, 6627, Belo Horizonte – MG. CEP 31270-901

João Mário Andrade Pinto, jm.andradepinto@gmail.com

Fundação Mineira de Educação e Cultura – R. Cobre, 200, Belo Horizonte – MG. CEP 30310-190

Abstract. Inspection of tubular heat exchanger bundles is a high complexity matter, due to the impossibility to do direct visual inspection or use conventional non-destructive techniques to evaluate the tubes integrity. Literature available recommends the use of ultrasonic IRIS (Internal Rotary Inspection System) technique for inspection of ferromagnetic tubes, but there is no standard procedure for the analysis of its results. This paper describes a methodology for IRIS results analysis, including sample sizing procedures, determination of regions with higher corrosion severity, calculation of tube critical thickness and directions to conduct a hypotheses test to evaluate the capability of operation of the tubular bundle. This methodology was applied in a practical case, in order to characterize the bundle integrity condition, quantify the reliability of this component and determine the necessity of maintenance. Efficiency of the sample size to represent the bundle as a whole was verified by means of *F* (of Fisher) and *t* (of Student) tests. Hypotheses tests were conducted in order to evaluate the necessity of substitute the tubes of the bundle. The case of study showed that poor maintenance decisions could be made, led by improper statistical approach on the IRIS results analysis.

Keywords: Inspection, Heat Exchanger, IRIS.

1. INTRODUCTION

Heat exchangers are equipments designed to provide the transfer of thermal energy between two fluids at different temperatures. According to Telles (2005), the most usual type of this equipment in petrochemical industry is the shell and tubes configuration, with straight bundle of tubes and floating head, Fig. 1. In this type of heat exchanger, the shell encloses the tubular bundle. Consequently, one fluid flows through the tubes and the other flow outside the tubes, and heat is transferred from one fluid to the other through the tube wall (Kreith and Goswami, 2005).

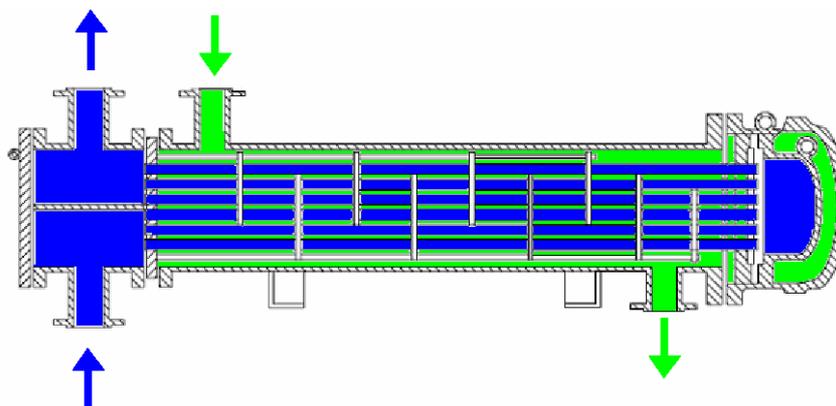


Figure 1 – Shell and tubes heat exchanger

The inspection of the tubular bundles is complicated due to the restricted access to the tubes caused by its complex layout, which does not allow direct visual inspection. Therefore, inspection is limited to the extraction of some tubes for sectioning and analysis, hammering the surrounding tubes, or to the employment of non-conventional non-destructive testing techniques, such as eddy current, remote field or rotary ultrasound (IRIS – Internal Rotary Inspection System). IRIS is the most indicated technique for inspection of tubes of ferromagnetic materials (Birring, 2001) and provides the minimal thickness of the tube tested. Minimal thickness is a parameter that quantitatively measures tube corrosion intensity.

The number of tubes in a bundle may vary significantly, ranging from tens to thousands. Therefore, in most cases, inspection of 100% of the tubes is impracticable, and it is usual to select a sample of tubes to be tested, representing the bundle as a whole. In spite of that practice, there are no standards that indicate a methodological process for this kind of service, and it is common that decisions could be made without an appropriate treatment of the data collected by the tests.

The present work has the objective of presenting a methodology to support such decisions. The methodology is applied to a study case where a decision of keeping (or not) a tubular bundle of a heat exchanger operating is required. A hypothesis test in a sample of its tubes, with determined significance level based on the operational criticalness of the equipment is applied and the results analyzed. Tests were then conducted to evaluate the efficiency of the sample to the representation of the tubular bundle as a whole and to identify regions of the bundle where could exist tubes with lower thickness.

2. EVALUATED EQUIPMENT

During programmed stop of production, after accumulated, approximately, 8,5 years of operation with corrosive fluids, the heat exchanger under study had been liberated for maintenance and inspection. This equipment has a straight tubular bundle with 630 tubes of carbon steel (ASTM A-179) of ¾” (19.05mm) nominal diameter and 2.11mm nominal thickness, distributed in two passes – 319 tubes in the lower pass (1st pass) and 311 in the upper pass (2nd pass).

The failure of the tubes causes contamination of the cooling water system and, by consequence, great perturbation in its treatment. Additionally, the liberation of this equipment for maintenance and correction of the failure causes issues in the process, been necessary the reduction of the processed load.

3. DATA ACQUISITION AND ANALYSIS

The inspection of the tubes was made by the application of IRIS technique, which is the most indicated for carbon steel and others ferromagnetic materials (Birring, 2001). This technique is based on the principle of measuring thickness using ultrasonic waves applying the pulse-eco method. An ultrasonic transducer of 15MHz is placed centered inside the tube and emits a sonic beam that reflects in a rotary mirror (1800rpm) toward the tube surface, making a 360° measurement of its thickness, Fig. 2. All the measurements made during a scan around the circumference are displayed on an oscilloscope screen and produces a stationary rectilinear picture of the cross section of the tube, Fig. 3. IRIS test is capable of detect pits with minimal diameter of 1,5mm and loss of thickness on inner or outer surface of the tube. The result of the IRIS test is the minimum thickness of the evaluated tube.

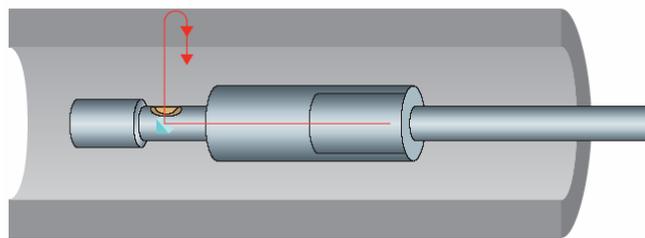


Figure 2 – Scheme of IRIS probe (Olympus, 2006).

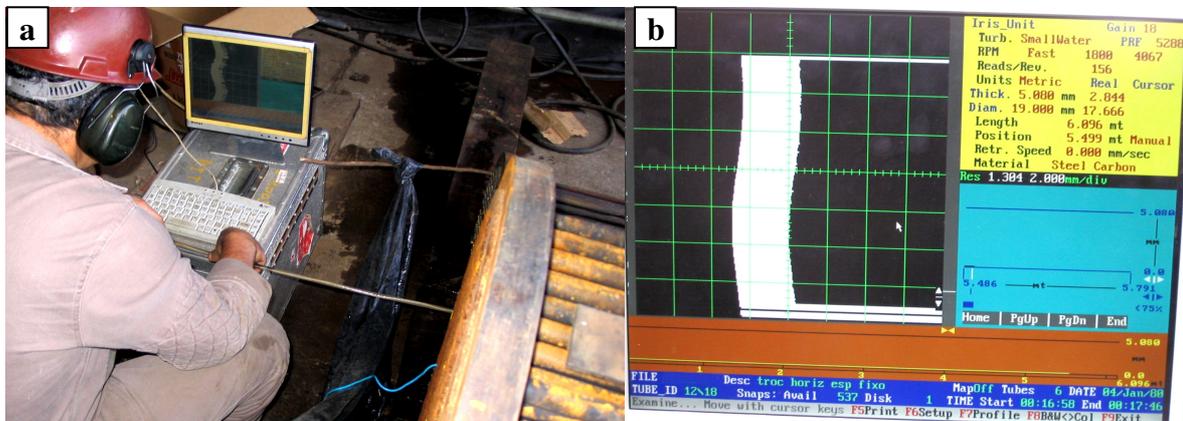


Figure 3 – IRIS execution and detail of the results screen. a) Inspector testing a tube of the bundle. b) Screen of IRIS equipment showing the cross section of the tube under test.

Initially, since there was no previous data about the variability of the tubes corrosion, a preliminary sample of the bundle was selected to be tested. It was defined that 40 randomly selected tubes, taking into account the criteria of achieving a sample greater than 30 elements and superior to 5% of the tube population. These requirements were used to represent the population of the minimal thickness of the tubes of the bundle as the normal distribution by the central limit theorem (CLT) (Cochran, 1977).

Although some recent papers of Barringer (2001) and Rodas *et al.* (2005) propose, respectively, the use of Gumbel Smallest distribution or Weibull distribution for the representation of the minimal thickness of the tubes of heat exchangers bundles, the adoption of the normal distribution is an economic and fast alternative, once that most of the commercial softwares has tools that can easily estimate the parameters of a normal distribution, dispensing the use of more elaborated and expensive solutions or softwares.

The assumption of normal distribution appears reasonably, once that, according to Laponi (2005), the CLT dictates that the arithmetic mean of the samples means is equal to the population mean and those samples means will be normally distributed around the population mean, independently of the real distribution of the population. Despite the IRIS results be the minimal thickness of the tested tube (and not the mean thickness), this change will only make the analysis more conservatively. It appears also as a recommended practice, once that the lack of precision in the historical data does not allow any estimation of the behavior of the population real distribution.

In order that the two passes had the same number of tested tubes, the preliminary sample was equally divided into two, with 20 tubes of each pass tested. Results of those tests are presented by the frequency histogram of Fig. 4, where the normal curves obtained by the characteristics parameters of the two samples (mean and standard deviation) were plotted, so that the visual comparison of its differences could be possible.

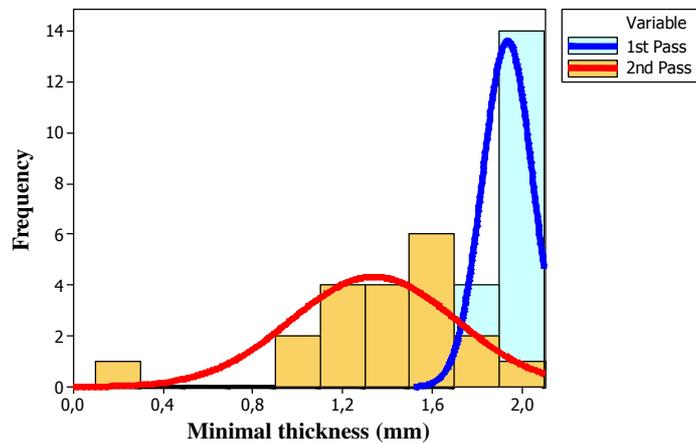


Figure 4 – Frequency histogram and normal distribution curves for the preliminary samples of 1st and 2nd passes.

The expressive difference between the two normal distributions originated by the preliminary samples (Fig. 4) suggests that the loss of thickness in the 2nd pass is more intense. To confirm the relevance of that hypothesis, the homogeneity of the samples was verified through the use of the *F* test of Fisher, for comparison of samples variances, and of the *t* test of Student, for the comparison of the samples means (Montgomery and Runger, 2003). Results are respectively presented on Tab. 1, and Tab. 2. The one-sided and two-sided notations refer to the kind of evaluation used: if it was consider the left or both tails of the distribution, respectively.

Table 1 – *F* test: Comparison of variances of preliminaries samples

	<i>1st Pass</i>	<i>2nd Pass</i>
Mean (mm)	1.9	1.3
Variance (mm²)	0.01	0.14
F statistic		0.09
P(F<=f) one-sided		2.40E-06
Critical F one-sided (Fo)		0.45

Table 2 – *t* test: Comparison of samples means for distinct variances

	<i>1st Pass</i>	<i>2nd Pass</i>
Mean (mm)	1.9	1.3
Variance (mm²)	0.01	0.14
t statistic		-4.67
P(T<=t) two-sided		1.07E-04
Critical t two-sided (T_o)		2.07

Those two tests confirm the hypothesis of the existence of distinct corrosion rates between the passes, since $F_o > F$ and $T_o > T$, which means that there are sufficient evidences that the variances and the means of the samples were proceeded from distinct populations.

The population of tubes of the 2nd pass, subjected to higher corrosion rates, was considered the critical population and selected to represent the bundle as whole, conservatively, because it had presented lower minimal thickness mean and greater sample variance

To define a sample that represents the whole bundle in an effective way, it was considered the necessity to keep the value of the sample standard error below 0,1mm (error associated to the IRIS measurement), in addition to the criteria of CLT of achieving a sample greater than 30 elements and superior to 5% of the tube population, as mentioned before. For this reason, it was conducted a complementary sampling of 38 tubes of the 2nd pass (critical population).

That sampling increase resulted in the reduction of the sample standard error from 0,2mm to 0,1mm. The results of the tests and the reduction in the sample variability to satisfactory level are represented by the confidence intervals diagram at Fig. 5, where the grouped sampling refers to the union of the results of preliminary and complementary sampling. The complementary sampling did not disturb the sample mean and reduced the sample variance of the critical population.

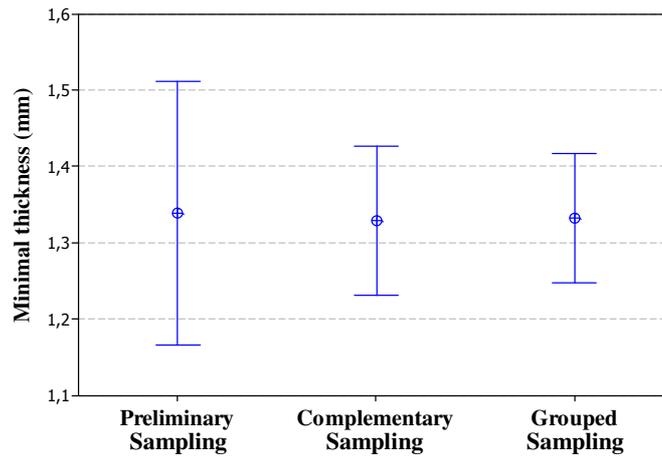


Figure 5 – Confidence intervals for a confidence level of 95% (critical population - 2nd pass).

4. HYPOTHESES TEST

After the data acquisition and analysis, it was formulated a test to verify if the hypothesis of the minimal thickness mean of the tubes of the bundle (μ) could be considered significantly higher than a determined value of critical remainder thickness (e_{crit}), calculated to minimize the possibility of a tube failure during the next campaign. The value of e_{crit} was defined by Eq. (1), where t_c is the predicted time for the next campaign, t_o is the accumulated bundle time operation, e_n is the nominal thickness of the tubes and e_{min} is the minimum thickness obtained by the IRIS tests of the critical population. The factor 1.5 takes part in the equation as a safety factor for possible operational variations that can modify the actual corrosion rate. For the case in study, it was considered a campaign of 5 years and the value of e_{crit} resulted in 1,8mm, based on Eq. (1).

$$e_{crit} = 1.5 * (t_c / t_o) * (e_n - e_m) \quad (1)$$

The hypotheses to be tested were defined as Eq. (2) and Eq. (3), where H_o is the null hypothesis and H_1 is the alternative hypothesis.

$$H_o: \mu < e_{crit} \quad (2)$$

$$H_1: \mu \geq e_{crit} \tag{3}$$

By the CLT, it is expected that the minimal thickness mean of the tubes be approximately equals to the sample minimal thickness mean of the bundle (e_m), that is, $\mu \approx e_m$.

Based on Eq. (2) and (3), a type I error – reject H_0 when it is actually true, will provoke the unnecessary replacement of the bundle tubes. A type II error – do not reject H_0 when it is actually false, will imply in return to operation a bundle that has a high probability of fail during the next campaign, witch is clearly more severe.

In order to apply the test, it was defined the following test statistics:

- $Z_{(\alpha)}$ – test statistic of the standardized normal distribution, for the confidence level adopted (α). In the present case, it was adopted a confidence level of 0.1%, due to the difficulty in liberation of the equipment for maintenance and the great perturbation caused by the bundle failure.
- Z_o – test statistic defined as (Lapponi, 2005), defined by Eq. (4), where s is the sample standard deviation, N is the number of tubes of the population and n is the number of tubes of the sample (sample size).

$$Z_o = \frac{e_m - e_{crit}}{s/\sqrt{n}} \cdot \sqrt{\frac{N-1}{N-n}} \tag{4}$$

The hypotheses test is represented in Fig. 6, where the hatched area corresponds to the rejection area, that is, if Z_o is inside this area ($Z_o < Z_{(\alpha)}$), H_0 should be rejected and the tubes must be replaced, otherwise the bundle can return to operation keeping the tubes.

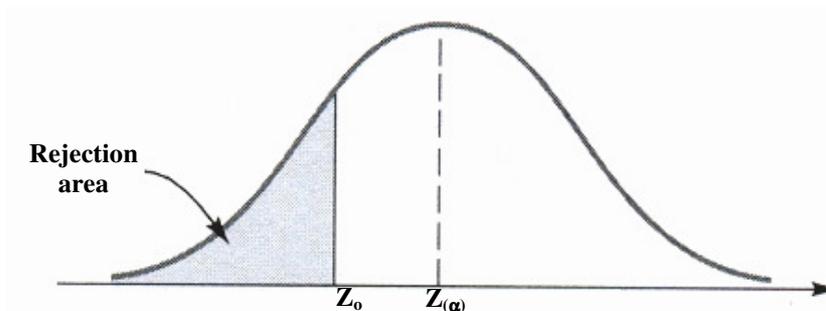


Figure 6 – Hypotheses test representation

The results of the hypotheses tests are presented in Tab. 3, where, for comparison, the test was applied for two distinct cases:

- in the first case it was considered only the data from the tests of the tubes of the critical population;
- in the second case it was considered the data from the preliminary samples grouped (1st and 2nd pass), simulating the situation where no procedure was used to identify the critical regions or to evaluate the sample size efficiency.

Table 3 – Hypotheses test results

	1 st case Critical population	2 nd case Preliminary sample
Z statistic	-3.09	-3.09
Critical Z statistic one-sided - Z_o	-11.26	-2.17
Should the bundle keep on operating (accept H_0)	No	Yes

The hypotheses tests demonstrate that there are evidences to make the substitution of the tubes of the bundle, once that the test statistics calculated for the critical population case (1st case) indicates the rejection of H_0 .

The comparison of the two evaluated cases demonstrate, clearly, the fundamental importance of an adequate statistical evaluation of the test data, since type II error would be committed if the inspection was limited to the preliminary sample (2nd case), that is, the bundle would be wrongly approved for operation and would have a high probability of failure during the next campaign.

5. CONCLUSIONS

This work presented the application of a methodology to the analysis of the results of IRIS tests to a specific tubular bundle, which allowed to:

- verify the efficiency of the sample size to represent the bundle as a whole, using criteria related to the CLT and to the define a maximum sample standard error acceptable;
- identify region with higher corrosion rate, by means of F test of Fisher, to compare the sample variances, and the t test of Student, to compare the sample means;
- evaluate the necessity of substitute the tubes of the bundle, by means of hypotheses tests.

The case of study showed that poor maintenance decisions could be made, led by improper statistical approach on the IRIS results analysis. The application of statistical procedures in the evaluation of IRIS results had shown to be the best way to reduce the subjectiveness of this service, guaranteeing the representativeness of the sampling and the accuracy of the decision make of replacing or not the tubes of the bundle.

This methodology allows, in addition, a greater knowledge of the equipment by the identification of the parameters of the normal distribution that represents the minimal thickness of the bundle. Those parameters are essentials to improve the reliability of the bundle and, in consequence, of the whole equipment. It can also reduce costs, once that allows a optimized use of the bundle. At last, those parameters can be used in the next interventions to increase the efficiency and precision of the sampling.

6. ACKNOWLEDGEMENTS

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