Chapter 12

Detection and Analysis of Petroleum Equipment Faults

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Additional information is available at the end of the chapter

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Abstract

The method fitness-for-service (FFS) provides the means by which the operator of a technical system can decide: It can continue to work safely, reducing of working parameters or stopping the equipment and reparation it. A case study concerning a natural gas pipeline is introduced. It brings some applicative aspects: the introduction of the failure probability as an indicator; the reduction of the degree of conservatism; a maintenance program based on pipeline intelligent gauge.

Keywords: fitness-for-service, pipeline, maintenance program

1. Introduction

While an equipment (pressure vessel, pipeline, tank, etc.) is pressurized and has a certain state of degradation, the operator must decide: Whether it can continue to work safely, reducing the working parameters or the equipment must be stopped and refurbished, avoiding injury of the personnel or other persons, and unexpected environmental accidents [1]. The method fitness-for-service (FFS) provides the means by which the operator can take these decisions based on reliable engineering knowledge.

The main factors that have to be considered when determining the applicability and limitations of a procedure for evaluating a pipeline by FFS are data available on pipeline, operation and maintenance history of the pipeline. For pipelines used to the transport of hydrocarbons standard, API 579 [2, 3] (whose assessment procedures are in turn based on the ASME B31G and the RSTRENG criteria [4]) recommends several levels of evaluation. Level 1—Evaluation procedures included in this level are aimed at securing conservative monitoring criteria that can be used with a minimum amount of information and inspections concerning the pipeline.

They can be implemented by the technical personnel of the user. Level 2—Evaluation procedures included in this level are designed to ensure a more detailed assessment, which leads to more precise results compared to Level 1 assessment. In this level, the information from inspections is consistent with those provided for Level 1, but using more laborious calculations for their interpretation. Level 2 assessment should normally be realized by technical staff with experience in assessments of this type. Level 3—Evaluation procedures included at this level are aimed at ensuring the accurate assessment, leading to more accurate results compared to Level 2 assessment. In this level, the most detailed information and recommended inspections of the pipeline are typically required, and analysis is based on numerical techniques such as finite element method or experimental techniques. It is expected that this level assessment to be carried out only by experts with proven experience and expertise in such evaluations. Many papers are devoted to this topic. Shekari et al. [5] have used FFS assessment methodology for process equipment to track and predict pitting corrosion. Pit density was modeled using a non-homogenous Poisson process and induction time for pit initiation is simulated as the realization of a Weibull process. The distributions of the operating pressure and the estimated burst pressure of the defected component are integrated with Monte Carlo simulations and first-order second-moment (FOSM) method to calculate the reliability index and probability of failure. Scano [6] has used FFS assessment for a pipeline connecting the boiler of a paper mill to the cogeneration turbine and the process headers. Because of the elevated number of in-service hours, an API 579-1 Level 3 assessment was required, and a FE shell model of the line was set up to evaluate plastic strain accumulation due to creep through a time-dependant inelastic analysis. The results of the assessment led to an estimate of 70,000 hours of residual life for the pipeline. Almeida et al. [7] have proposed a modeling of a pressure vessel under internal and external corrosion using the fitness-for-service (API 579). Non-destructive testing by ultrasound was used to obtain loss of thickness wall measurements for pressure vessel damaged and develop the modeling. The objective is to analyze and evaluate the values of maximum allowable working pressure (MAWP) provided by the fitness-for-service assessment using numerical thermal transient analysis using finite element. Janelle [8] has reviewed the technical basis for the fitness-for-service assessment procedures for general and local metal loss. Extensive validation of these procedures along with additional development was presented. The conclusions of the study are recommended as the best practices to be included in future versions of API 579. Adib-Ramezani et al. [9] have studied the notch stress intensity factor concept, and SINTAP structural integrity procedure is employed to assess gas pipelines integrity. The external longitudinal defects have been investigated via elastic-plastic finite element method results. The extracted evaluations are compared with the limit load analysis based on ASME B31G, modified ASME B31G, DNV RP-F101. The comparison among extracted safety factors exhibits that SINTAP predictions are located between lower and upper safety factor bounds. Ahammed [10] has used deterministic model to evaluate the remaining strength of corroded steel pipeline over time. This model evaluates the remaining strength of corroded steel pipeline over time. The model also can be used to evaluate the maximum allowable failure pressure of corroded pipelines. Ahammed [11] has developed previous calculation model. Because of the presence of nonlinearity in the limit state function and also of the presence of non-normal variables, the Level II advanced first-order second-moment iterative method is employed for carrying out reliability analyses. Li et al. [12] have used an original methodology for predicting corrosion remaining life of underground pipelines with a mechanically based

probabilistic model by taking effect of randomness into account in pipeline corrosion. The results show that the corrosion defect depth and radial corrosion rate are the key factors influencing pipeline failure probability and remaining life. Netto et al. [13] have studied the effect of external corrosion defects via a series of small-scale experiments and through a nonlinear numerical model based on the finite element method. The model was used to determine the burst pressure as a function of material and geometric parameters of different pipelines and defects. Teixeira et al. [14] have evaluated the reliability of pipelines with corrosion defects subjected to internal pressure using the first-order reliability method (FORM). The limit-state function is defined based on the results of a series of small-scale experiments and three-dimensional non-linear finite element analysis of the burst pressure of intact and corroded pipelines. Minescu and Pana [15] have demonstrated the equivalence of the results obtained with the assessments procedures API 579 and ASME B31G over a pipeline transport system. In Section2.1.1, there are revealed the novelty aspects of this work. In conclusion, it should be said that the FFS method is extensively applied in industry in various fields; the progress of theoretical and experimental applied methods has improved the application results; method deserves to be consistently applied in technologic systems.

2. Using fitness-for-service assessment method—case study

2.1. Characteristics of fitness-for-service method

A case study concerning a natural gas pipeline is introduced for example. In this evaluation, which is essentially a FFS method, different ways are suggested from those used in the standards DNV RP 101 [16], API 579 and ASME B31G.National Regulatory Authority for Energy (NRAE) from Romania supervises the activity of the transmission system operators (TSO) for petroleum products. Such the transporters are obliged to fulfill certain procedures. Effectiveness of these procedures is measured by several indicators as the number of defects per km of pipeline; accidents found during operation; accidents caused by third parties; complaints of customers, etc. [17]. Pipeline (both for liquid petroleum products and for the gaseous hydrocarbons) from Romania is inspected by pipeline intelligent gauge (PIG) technology. Appreciation of the failure limit of a pipeline (for the case when the pipeline destruction is possible because of corrosion defects) can be done in two ways [18, 19]:

a. It makes the difference between failure pressure and the pressure of the operating.

b. It makes the difference between the thickness of the resistance (usually 80% of the pipe wall thickness) and depth of corrosion of corresponding to the defect that was detected in the pipeline wall.

Mustaffa et al. [20] have achieved an excellent review over limit state methods. Recently, some authors have developed models for the limit state (based on similarity theory) including the geometrical parameters of the pipeline, geometrical characteristics of major defects and pipeline operating conditions. A good study over the subject has accomplished by Zecheru et al. [21]. This is another way of estimation of the limit state, which was added to the two methods above. Caleyo et al. [18] have used the first-order second-moment iterative reliability method, and the Monte Carlo integration technique and the first-order Taylor series expansion of the

limit state function (LSF) are used in order to estimate the probability of failure associated with each corrosion defect over time. De Leon and Macias [19] have studied the reliability of a pipeline using FFS method. Several degrees of spatial correlation are assumed for the corrosion in determined segments of a pipeline, and their effects on the global reliability are examined. The pipeline is assumed to be a series system. The failure mode is considered to be controlled by the stresses due to internal pressure and the presence of corrosion. Component reliability is calculated by first-order second-moment approximations. The defects identification and appreciation of their evolution in time are valuable if it ends with a maintenance program indicating when and where to intervene to repair the pipeline, before producing an unwanted incident. The application further described has the following enhancements:

a. Provide a maintenance program based on the information during the inspection. This program has implemented since 2008 in TSO main companies from Romania Transgaz SA and Conpet SA.

b. In the theoretical model further exposed, the operating pressure was considered in the place where the fault occurs. Considering the pressure at the defect position reduces the degree of conservatism of the evaluation method.

c. Based on geometrical parameters, characteristics of major defects and pipeline operating conditions can calculate the probability of pipeline failure. This indicator is better than traditional indicators used by NRAE as it includes measurement results PIG.

2.2. Theoretical model

The appreciation of the limit state of a pipeline can be made by several methods [12, 18, 20], from which, in this paper, it was used the difference between the failure pressure of the pipeline PF_i corresponding to the defect i and the pressure of operating PO_i corresponding to the position of this defect:

$$Z_i = PF_i - PO_i. \tag{1}$$

The pressure of failure has more computing methods [4, 15, 16], from which, in this paper, it was used for exemplification the RSTRENG[1] method:

$$PF_i = \frac{2 \cdot UTS \cdot t}{D}\left(1 - \frac{d_i}{t \cdot M_i}\right), \tag{2}$$

$$M_i = \sqrt{1 + 0.63\left(\frac{l_i}{D}\right)^2\left(\frac{D}{t_i}\right) - 0.0034\left(\frac{l_i}{D}\right)^4\left(\frac{D}{t_i}\right)^2}, \tag{3}$$

where UTS is the ultimate tensile strength of the material of the pipeline; t_i is the wall thickness of the pipeline at defect location; D is the outer diameter of the pipeline; d_i is the depth of the defect; M_i the bulging factor(Folias); l_i is the length of the defect. The pressure of operating at

[1]Remaining Strength of Corroded Pipe (RSTRENG) assessment procedure, www.rstreng.com.

the defect position PO_i was calculated considering a linear variation of the pressure along the pipeline:

$$PO_i = PO_{start} - \frac{PO_{start} - PO_{end}}{L_p} L_i, \tag{4}$$

where PO_{start} is the operating pressure at the inlet of the pipeline; PO_{end} is the pressure at the outlet of the pipeline; L_p is the length of the pipeline; L_i is the distance from the beginning of the pipe at the location of the defect i. The values used in the relations above are l_i, d_i, t_i, L_i from the results of the PIG inspection; D, PO, UTS probabilistic variables (the mean value is known and the value of standard deviation is based on statistical studies [15, 21–23] **Table 4**). To calculate the probability of failure FP_i of the defect i, the Monte Carlo method [5, 18] was used. If the difference expressed by Eq. (1) is positive, the situation is favorable and the pipeline does not fail. If the difference is less or equal to zero, the pipeline fails. We note the number of attempts for $Z \leq 0$ with n_d. The probability of failure expressed for a number of N tests performed is as follows:

$$FP_i = \frac{n_d}{N}. \tag{5}$$

For a pipeline with a number of defects n, it is considered a system in series with n critical elements, and the probability of failure FP is [19]:

$$FP = 1 - \prod_{i=1}^{n} (1 - FP_i). \tag{6}$$

The variation of the size of defect over time (the time is denoted with T) was calculated with the relations:

$$l_i(T) = l_i(T_0) - V_{a,i}(T - T_0), \tag{7}$$

$$d_i(T) = d_i(T_0) - V_{r,i}(T - T_0), \tag{8}$$

where T_0 is the time of inspection of the pipeline. We considered the values of the corrosion rates (at each defect i) in the axial direction $V_{a,i}$ and in the radial direction $V_{r,i}$, and their values were determined at the time of the inspection (and constant further considered):

$$V_{a,i} = \frac{l_i(T_0)}{T_0}, \tag{9}$$

$$V_{r,i} = \frac{d_i(T_0)}{T_0}. \tag{10}$$

2.3. Results obtained

For example, it was used a steel pipeline (52 × SR 11082 material and 57km length) located between cities Constanta and Ploiesti. The example is extracted from research work [23]. The

pipeline was inspected using an ultrasound method [the usual methods of inspection there are magnetic flux and ultrasound and the device is named pipeline intelligent gauge (PIG)], **Figure 1**. We used for the inspection a20″ Ultrasonic Intelligent Pig, Korsonic 324, with the following specifications: PIG diameter 350 mm; body length 850 mm; overall pig length 950 mm; temperature max. for PIG 65°C; pressure max. 50 barg; min. bend radius 3 × Internal diameter; transducer frequency 0.5 MHz; transducer focus plane; min. measurable thk 3 mm; max. measurable thk 0.7 m; inspection sensitivity ±0.1 mm; repetition rate 2300 kHz; inspection speed Max. 5 m/min; max. inspection capacity 120 h; axial sampling distance min. 3 mm; circumferential resolution 5.5 mm. The ultrasonic signal is induced directly in the wall to be inspected, EMAT technology. It notes that the procedure for determining defects of the pipelines uses three-dimensional images that are offered to users in the form of Excel files, **Table 1**. These images were obtained over the last 20 years with a precision increasingly better. The instrument measures the thickness of the pipeline in a network of points, **Figure 2**. The image is reported as an Excel file. An example is shown in **Table 1**. As the beneficiary of the contract imposed certain conditions of confidentiality, they have been used data from a pipeline segment of 8622 m. So the probability of failure calculation refers only to this segment and not to the entire pipeline. The total number of defects found was 56.824. These can be classified after the geometrical characteristics (**Table 2**) and the cause that determined the defect: manufacturing, construction, corrosion, mechanical damage and repair (**Table 3**, column 10).

The defects characteristics were included in a data matrix size (56,824; 10) each row representing a defect, **Table 3**. The significance of columns of the data matrix is as follows: the distance at which the welds are located on the pipeline segment measured from the start of the pipeline

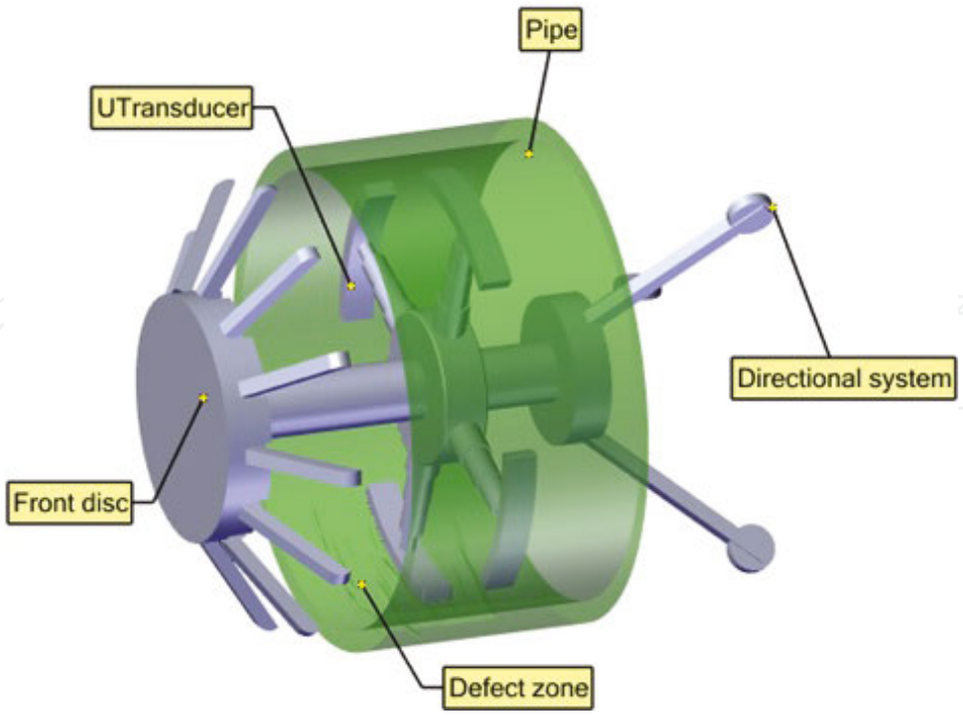

Figure 1. Pipeline intelligent gauge — tip Korsonic 324 – Cala & Cdria Pipeline Services Company Ltd: Ultrasonic Transducer (UT) is mounted inside the inspection device.

	Axial direction									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
1	14.20	14.00	13.00	13.00	13.10	13.20	13.60	14.20	14.20	14.20
2	13.20	13.20	13.40	13.40	13.40	13.40	13.60	14.00	14.00	13.40
3	13.60	13.40	13.40	13.80	13.60	13.60	13.80	13.80	13.60	13.20
4	13.60	13.80	13.40	13.60	13.60	13.60	13.40	13.20	13.20	13.00
5	13.60	13.67	13.73	13.80	13.60	13.40	12.80	12.80	12.80	11.60
6	13.50	13.30	12.95	12.60	12.80	13.00	12.80	11.60	11.80	10.80
7	13.40	14.00	13.00	12.80	12.80	12.57	12.33	12.40	11.80	11.60
8	13.60	12.80	13.00	12.80	12.45	12.10	11.87	11.80	11.40	11.00
9	13.80	13.80	13.40	13.20	12.60	12.00	11.40	11.40	11.20	11.00
10	13.80	13.20	14.20	14.00	13.00	12.00	11.20	11.50	11.20	11.00
11	13.60	13.40	13.60	12.80	12.80	12.80	13.40	11.60	11.30	11.00
12	13.40	13.00	12.60	12.10	11.60	11.70	11.80	11.60	11.40	11.10
13	13.40	13.40	13.60	13.80	14.00	13.60	12.80	13.60	12.00	11.50
14	13.60	13.80	13.60	13.40	13.60	13.60	13.80	13.40	12.60	12.10
15	13.60	13.70	13.75	13.80	13.80	13.80	13.60	13.60	13.20	13.40
16	13.60	13.60	13.80	13.80	13.60	13.40	13.40	13.40	13.40	13.40
17	13.60	13.60	13.80	14.20	13.60	13.30	13.50	13.40	13.60	13.20
18	13.60	13.80	13.60	13.60	13.60	13.20	13.60	13.40	13.20	13.00
19	13.40	13.60	13.80	13.50	13.20	13.40	13.40	13.40	13.40	13.40
ACP	13.20	12.80	12.60	12.10	11.60	11.70	11.20	11.40	11.20	10.80
	11	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
1	12.80	14.20	14.00	13.60	13.40	13.40	14.20	14.20	14.20	14.20
2	13.20	13.00	14.20	13.60	13.20	13.00	13.40	13.00	13.20	13.20
3	13.20	13.20	13.00	13.20	13.40	13.00	13.40	13.60	13.40	13.40
4	13.00	13.00	13.20	13.40	13.40	13.20	13.60	13.40	13.20	13.20
5	11.00	10.80	10.60	11.00	11.40	12.28	13.16	13.50	13.10	13.00
6	10.60	11.00	12.60	11.00	11.30	11.76	12.68	13.60	13.00	13.20
7	11.40	11.20	11.00	11.00	11.20	11.20	11.51	11.83	11.53	11.96
8	11.40	11.00	10.80	10.80	11.00	10.47	10.09	10.06	10.07	10.73
9	11.70	11.70	11.60	11.70	10.56	9.73	9.36	8.98	8.60	9.83
10	11.70	12.40	12.40	11.25	10.12	9.00	8.80	8.60	8.40	9.06
11	11.00	11.00	11.00	10.80	9.88	8.96	8.44	8.32	8.20	8.00
12	10.80	10.60	10.80	10.40	9.60	8.80	8.00	8.67	9.33	10.85
13	11.20	11.40	11.00	11.40	11.07	10.27	9.66	9.80	10.47	11.24

	Axial direction									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
14	11.60	11.60	12.00	12.40	12.53	11.80	11.31	11.27	11.60	12.32
15	13.60	13.60	13.60	13.40	14.00	13.40	12.97	12.73	13.07	13.40
16	13.60	13.40	13.40	14.20	13.40	13.40	13.80	14.20	13.40	13.40
17	14.20	13.20	13.20	13.20	13.60	13.60	13.40	13.60	13.30	13.90
18	13.80	13.40	13.40	13.40	13.20	13.40	13.50	13.00	13.20	14.20
19	13.40	13.60	13.40	13.20	13.60	13.40	13.60	13.60	13.60	13.60
ACP	10.60	10.60	10.60	10.40	9.60	8.80	8.00	8.32	8.20	8.00
	21	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**
1	14.20	13.40	13.20	14.20	13.90	13.60	13.60	14.20	14.20	14.20
2	13.20	13.00	13.00	14.20	13.20	13.20	13.70	14.20	14.20	13.60
3	13.20	13.20	13.60	13.20	13.40	13.40	13.40	13.00	12.40	13.40
4	13.40	13.80	13.20	13.20	13.40	13.80	13.30	13.40	13.40	13.40
5	13.00	13.00	12.80	13.60	13.40	13.60	13.20	13.20	13.20	13.60
6	13.00	12.80	13.60	13.00	13.20	13.40	13.20	13.20	13.20	13.20
7	12.85	13.20	14.20	13.20	13.40	13.20	13.40	13.40	14.00	13.40
8	11.62	12.51	13.40	13.40	13.20	13.60	13.20	13.80	13.60	13.40
9	11.05	12.28	13.50	13.50	13.50	14.00	13.60	13.60	13.60	13.60
10	10.57	12.09	13.60	13.60	13.80	13.40	13.40	13.40	13.60	13.20
11	10.85	13.70	13.00	13.20	13.40	13.40	13.60	13.20	13.40	14.20
12	13.80	13.20	13.40	13.40	13.40	13.40	13.60	13.90	14.20	13.40
13	13.50	13.20	13.40	13.40	13.80	13.60	13.60	13.60	13.60	13.40
14	13.20	13.60	13.80	13.80	13.60	13.40	13.60	14.20	13.40	13.30
15	13.60	13.60	13.90	14.20	13.60	13.40	13.47	13.80	13.20	13.20
16	13.40	13.80	13.80	13.60	13.20	13.50	13.47	13.40	13.40	13.90
17	14.20	14.00	13.80	13.40	13.40	13.60	13.60	13.40	13.30	13.55
18	14.20	13.40	13.40	13.40	13.60	13.40	13.30	13.20	13.20	13.20
19	13.60	13.40	13.40	13.80	13.20	13.40	13.20	13.25	13.30	13.35
ACP	10.57	12.09	12.80	13.00	13.20	13.20	13.20	13.00	12.40	13.20

	31	**CCP**	**Defect characteristics**
1	13.40	12.80	ACP axial critical profile
2	13.60	13.00	CCP circumferential critical profile
3	13.20	12.40	Pressure max. 6.4 MPa; Temperature 20°; Internal diameter 473.6 mm
4	13.20	13.00	Nominal thickness 14.2 mm; Uniform loss of material LOSS 0.77 mm
5	13.20	10.60	Corrosion allowance FCA 1.524 mm; API 5L X-52 steel material

	31	CCP	Defect characteristics
6	13.30	10.60	Conventional extension limit: Sc = 360 MPa
7	13.40	11.00	Ultimate tensile strength of thematerial 490–620 MPa
8	13.40	10.06	Percentage elongation after break: A2 in = 22%;
9	13.40	8.60	Modulus of elasticity (Young): E = 205,000 MPa
10	13.50	8.40	Transverse contraction coefficient (Poisson); μ = 0.3
11	13.60	8.00	Safety coefficient Cs = 1.4
12	13.60	8.00	Allowable resistance Sa = Sc/cs = 344.75/1.4 = 257.14 MPa
13	13.60	9.66	Distance to the nearest discontinuity Lmsd = 700 mm
14	13.60	11.27	RSFa accepted allowable resistance coefficient = 0.9
15	13.60	12.73	
16	13.00	13.00	
17	13.10	13.10	
18	13.20	13.00	
19	13.40	13.20	
ACP	13.00		

Table 1. The matrix of the measured thicknesses corresponding to a specific defect (**Figure 2**).

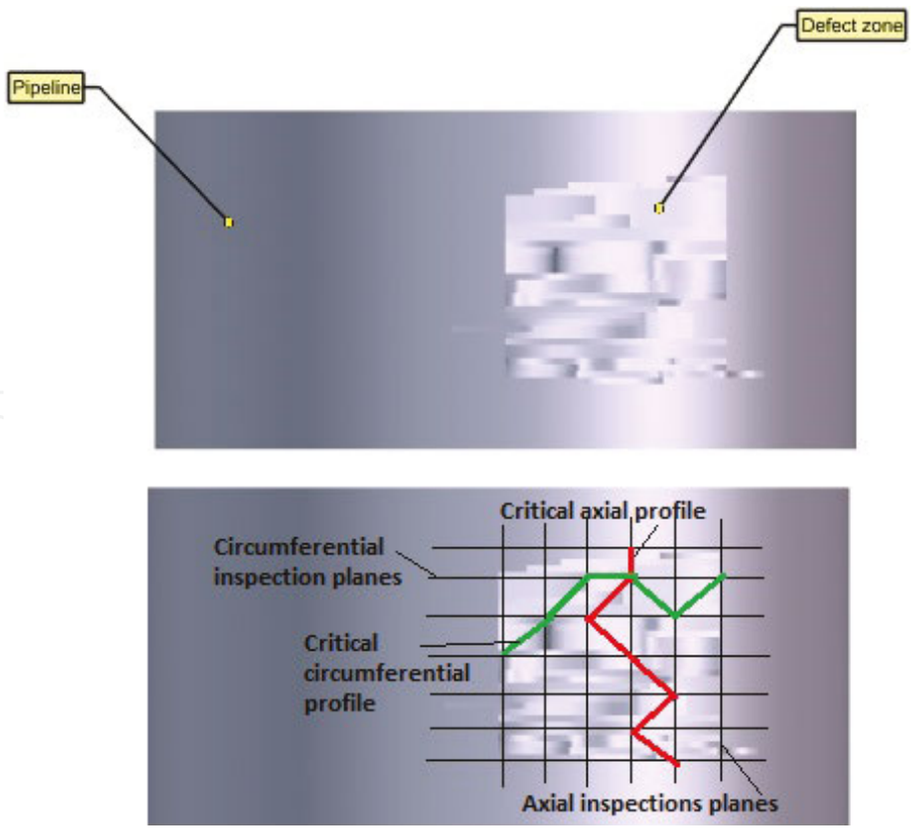

Figure 2. The results of the inspection: tridimensional images of the defects.

(column 1), distance between weld and defect (column 2), the distance from the defect to equipment (column 3), the thickness of the wall of the pipeline at defect position (column 4), clock orientation (column 5), the length of the defect (column 6), the width of the defect (column 7), maximum depth of the defect (column 8), average depth of the defect (column 9), the type of defect (as the cause) (column 10). Where eliminated from the analysis 1662 defects whose causes (column 10) were manufacture, construction activities, repairs, accidental interventions because: They have shallow depths below 20% of the thickness of the pipeline and not due to corrosion, so their development in time is not probable. The remaining 55,162 defects are the following types (**Table 2**): general metal loss, spots, axial and circumferential groove.

As it is seen a large number 55,162 corrosion defects reported by the inspection, but many of them are superficial. Defects have been chosen only to the depth of more than 20% of the thickness the pipeline; their number is 212. The geometrical elements of these defects are in **Table 3**. For the variables *D, UTS* and *PO* we considered the values from **Table 4**, [11, 21, 23]. After 8 years of operation ($T_0 = 8$ years), the probability of failure *FP* versus operating pressure is represented in **Figure 3** (calculated at the end of each working year).

The fault location is important to value of the probability of failure FP. If we consider the operating pressure of the pipeline: FP is 0.03 for PO of 5 MPa and equal to 1 for the other pressures of operation of the pipeline. If we consider pipeline pressure at fault position then for PO of 5 and 7 MPa, FP is zero, at 9 MPa FP is equal with 0.24 and equal with 1 at 11, 13 and 15 MPa. If we choose the limit of the probability of failure of 0.5 (highly conservative methods of calculus [4] justifies this value), the first case of assessment tells us that at the work pressures above 5 MPa we could not use the pipeline. The second case of assessment tells us that we can use the pipeline at the pressures of 7 and 9 MPa, too. We have thus a lower degree of conservatism. Based on the considerations we made, it can be appreciated the defect evolution in time. It is true that these considerations include several simplifying assumptions, but also includes the results of PIG measurements. In the situation where it is considered the pipeline

Defect type	**Characteristics**
General loss of metal	$\{[w \geq 3A] \text{ and } [l \geq 3A]\}$
Circumferential notch	$\{[w \geq 1A] \text{ and } [0 < l < A]\}$
Axial groove	$\left\{[1A \leq w < 3A] \text{ and } \left[\frac{l}{w} \geq 2\right]\right\}$
Circumferential groove	$\left\{\left[\frac{l}{w} \leq 0.5A\right] \text{ and } [1A \leq l < 3A]\right\}$
Pin	$\{[0 < w < 1A] \text{ and } [0 < l < 1A]\}$
Axial notch	$\{[0 < w < 1A] \text{ and } [l \geq 1A]\}$
Spots	$\left\{\begin{array}{c}[1A \leq w < 6A] \text{ and } [1A \leq l < 6A] \text{ and } \left[0.5 < \frac{l}{w} < 2\right] \\ \text{and not } ([w \geq 3A] \text{ and } [l \geq 3A])\end{array}\right\}$

The geometric parameter A is defined as follows: if $0 < t < 10$ mm then $A = 10$ mm, if $t \geq 10$ mm, then $A = t$, according to Ref. [2]; l defectlength; w defectwidth.

Table 2. The classification of corrosion defects after geometrical aspect.

Reference distance of welding [m]	Distance of defect to welding [m]	Distance to equipment [m]	Wall thickness [mm]	Clock orientation of defect	Length of defectL [mm]	Width of defectL [mm]	Maximum depth of defect [%]	Average depth of defect [%]	Type of defect
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
19.1	−6.12	2	14.2	8:02	23	18	8	5	Axial groove
28.04	−1.39	1.4	14.2	12:14	11	18	14	10	Axial groove

Table 3. The Excel file filled with data analysis elements (values of ultrasonic inspection).

Variable	Distribution law	Mean value	Standard deviation
Outer Diameter, *D*	Normal	508 [mm]	14 [mm]
Ultimate tensile strength of thematerial, UTS	Normal	517 [MPa]	30 [MPa]
Pressure of operating, PO	Gumbel	Steps 5; 7; 9; 11; 13; 15 [MPa]	0.1 [MPa]

Table 4. The probabilistic variables used in the simulation.

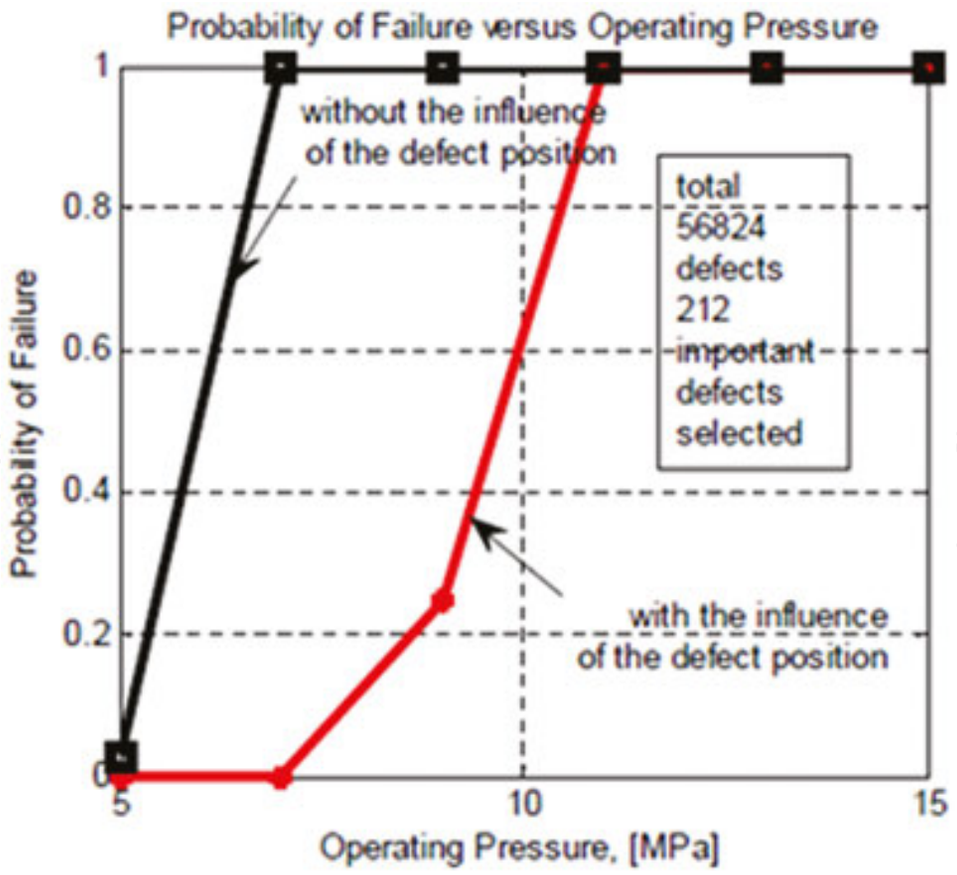

Figure 3. The influence of the defect position versus the probability of failure.

pressure at the defect position was represented the progress of defect probability of failure in time (with a step of 2 years) **Figure 4**. If the pipeline operating pressure is 5 MPa is observed that after 14 years FP grow rapidly, showing that the operator should perform repairs to the system. In the case of operating pressure of 7 MPa since the 12th year of exploitation, FP increases of and between years 12th to 14th FP rises further reaching value 1. Operation of the pipeline to 9 MPa shows a probability of failure which reaches 1 (sure failure) between years from 8th to 12th. Obviously, in situations where the probability of failure is high (it has chosen the 0.5 limit) should intervene to repair the pipeline. By choosing this limit, some defects become critical. The list of defects which should be repaired is given in **Table 5**. If these defects are repaired, then the pipeline FP falls, and it can be used safely for many years, and over a range of operating pressures as shown in **Figure 5**. The method described above was implemented on programs (in Matlab) made by the authors [22, 23]. It is generated a list of defects to be repaired every year, **Table 5** (an example for two pressures 5 and 7 MPa). If the number of the defects is high, an economic analysis of whether a repair or a replacement of the section of the pipeline is required. So we have a procedure of action based on the results of inspection and the accomplished analysis, useful in the maintenance process. The effect of the repair is seen immediately; the pipeline is less likely to fail. However, at higher operating

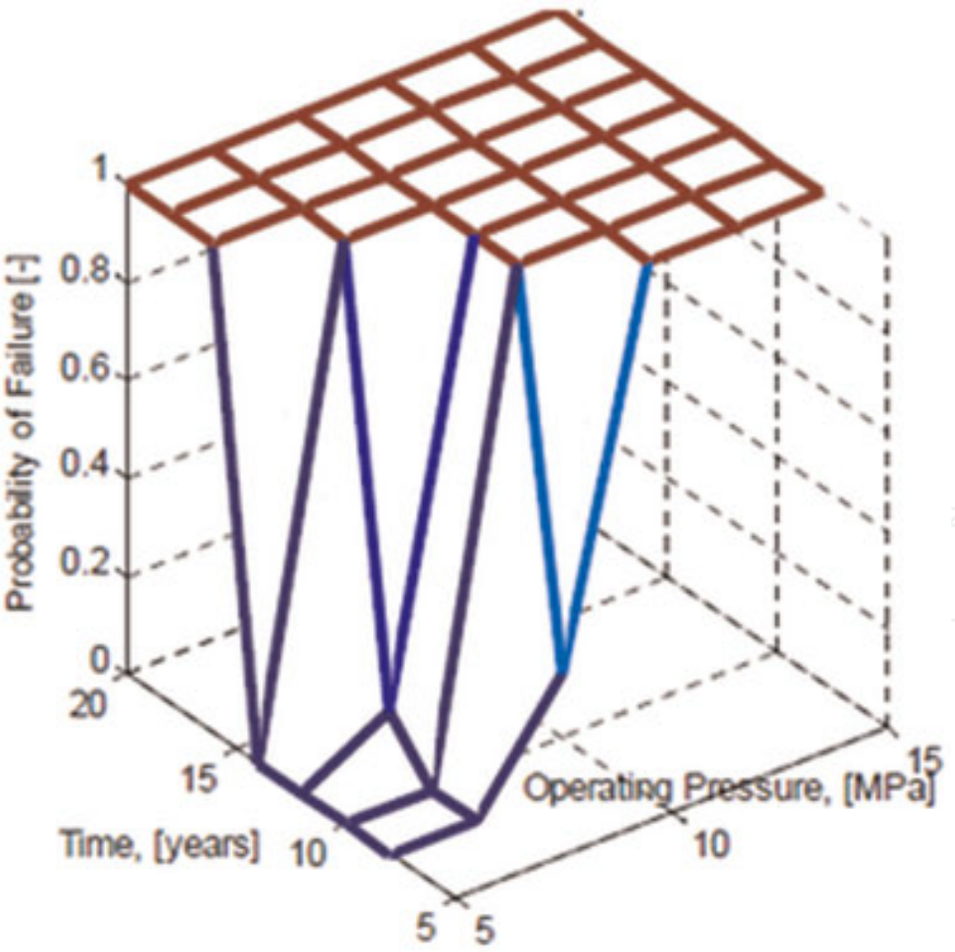

Figure 4. Probability of failure depending on operating pressure and time, if the critical defects are not remedied.

Year	The working pressure 5 [MPa], the number of defects to be repaired 15	The working pressure 7 [MPa], the number of defects to be repaired 33
	The number[1] of the defect repaired	**The number of the defect repaired**
12	–	37 102
14	–	22 25 104 187
16	37 102 104 187	9 16 45 57 61 99 100 127
18	22 25 57	19 50 72 75 111 126 155 166
20	45 50 61 99 100 127 166 205	17 35 51 55 91 101 114 154 162 165 205

[1]The defects are numbered from 1 to 212.

Table 5. List of the defects with the probability of failure greater than 0.5, which must be repaired at the beginning of each year (example of the maintenance program).

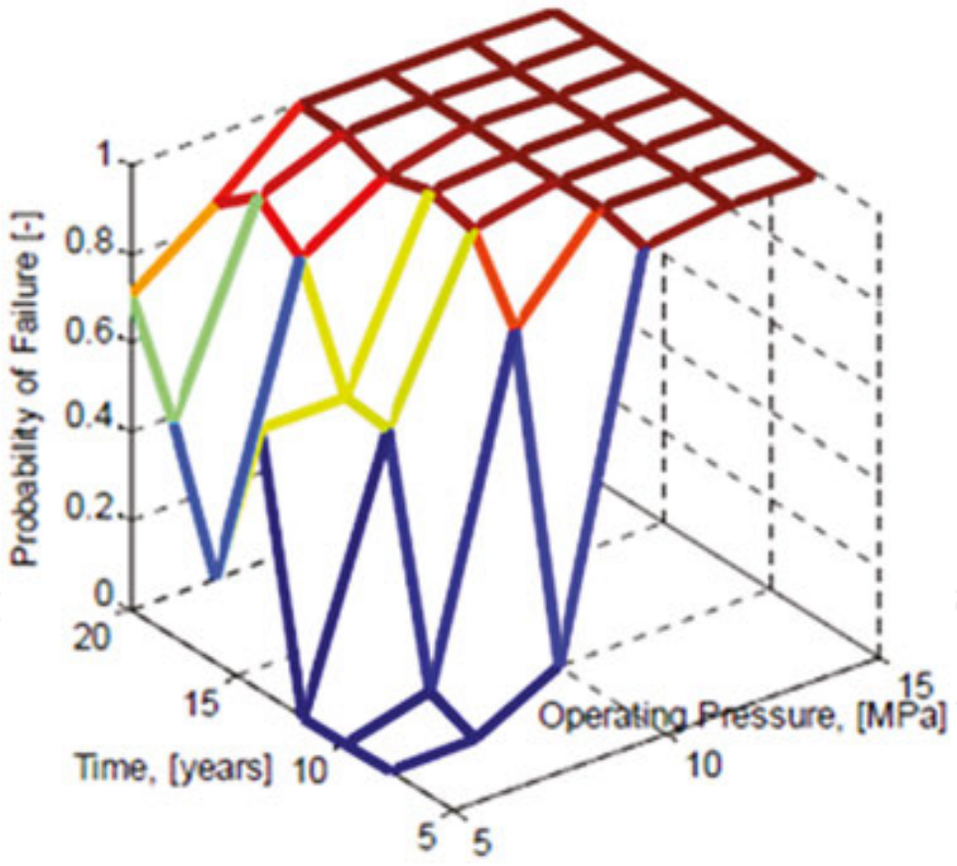

Figure 5. Probability of failure depending on operating pressure and time, when the critical defects are repaired.

pressure, the pipeline conditions lead to a FP equal to 1 regardless of its status. All theoretical models are tested on samples taken from the defective pipeline s. 2.4, to verify the accuracy of the assumptions used [23].

2.4. Experimental determination of pressure burst for the pipes with faults type losses of material

Experimental verification of the behavior of the mechanical elements of pipeline with defects of various kinds is one of the methods for establishing the reserve strength of mechanical resistance. It can draw conclusions about the level of trust that must be attached to the results of assessing the seriousness of defects by the available analytical methods. Studies should include up to burst pressure test of the pipe that have been identified local defects such as loss of material [8]. The following example shows how to perform a test (external diameter $De = 508$ mm, wall thickness $s = 6.3$ mm) of a specimen, which was taken from a section on which were discovered defects of the type material loss. **Figure 6** has revealed defects of the type of material loss that were discovered on that section after inspection with smart devices by type PIG. The geometrical characteristics of defects of the type material loss from the sample under test pressure are given in **Table 6**.

The sample for internal pressure testing consists of a fragment cut from a pipe and two bottoms dished welded ends, which were mounted two connections: the first for ventilation of the sample prior to pressurizing and subsequently for manometer mounting and the second for filling of the

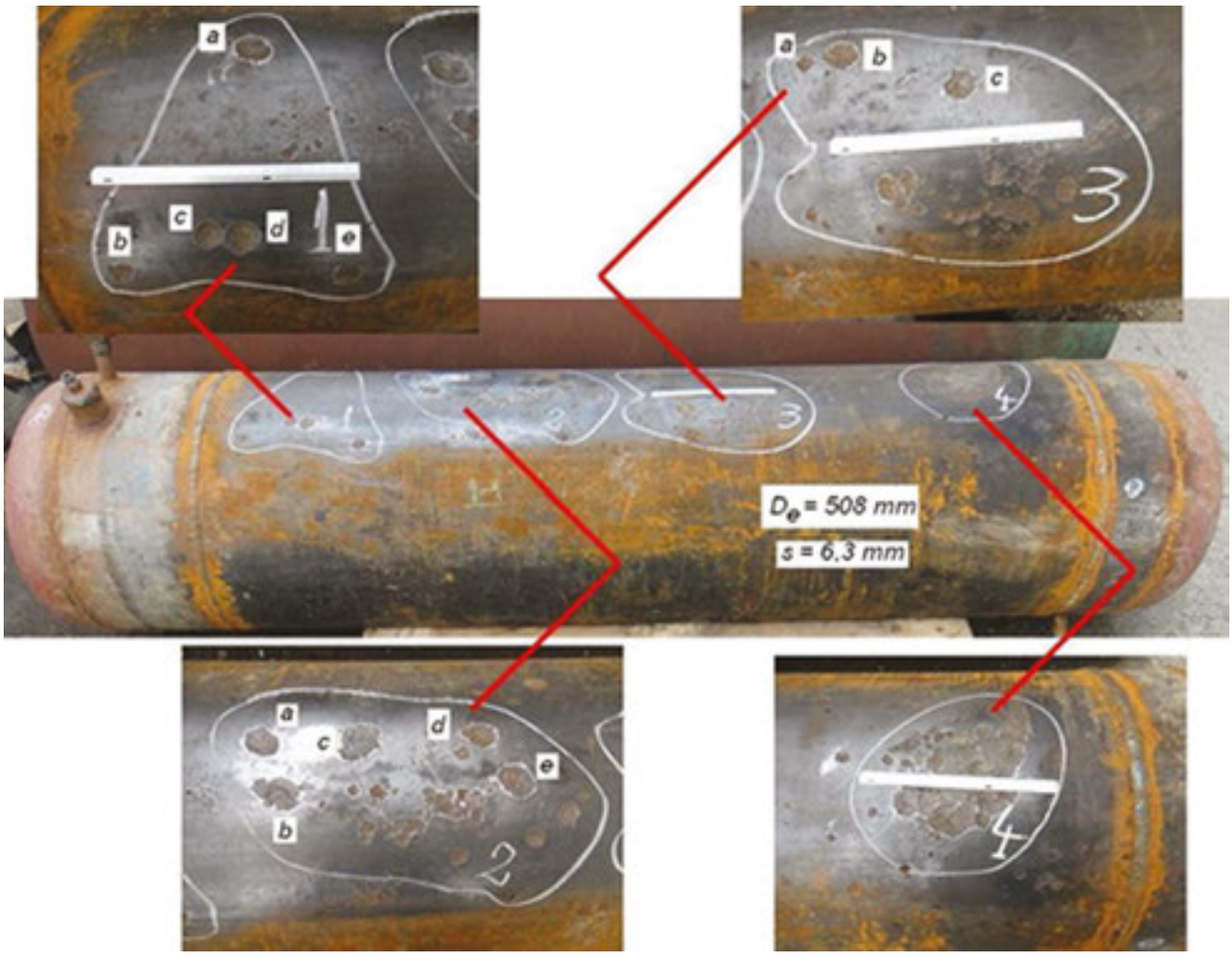

Figure 6. Defects loss of material from the sample being tested.

		Geometric characteristics of the defect		
Location area	**Defect code**	**Maximum depth, d, [mm]**	**Circumferential extension, l_c [mm]**	**Axial extension, l_a [mm]**
1	1a	3.3	35	30
	1b	1.7	25	25
	1c	2.6	25	25
	1d	3.1	30	30
	1e	2.2	25	25
2	2a	3.2	35	35
	2b	5.0	50	35
	2c*	**5.0**	**40**	**45**
	2d	3.6	40	30
	2e	3.9	40	35
3	3a	1.6	15	15
	3b	4.1	35	40
	3c	3.6	30	40
4	**4a****	**4**	**3.2 … 4.8**	**190**

*Defect to which the tenso resistive transducer was glued.
**Zone wherein the breaking of the sample occurred.

Table 6. The geometric characteristics of the defects type loss of material subjected to the burst pressure test.

sample with water and pressurizing it. The stand that has been tested the sample to internal pressure (up to burst) was conducted at the Petroleum—Gas University of Ploiesti and reproduce diagram in **Figure 7**, which presents the constructive elements: the high pressure pump and a platform working in the organization of the stand, **Figure 8**. While conducting the experiment, on the sample of pipeline were applied around the fault with code 2c (defect considered to be the most dangerous depending on the geometrical characteristics), transducers in two directions, circumferential direction TER 1 and the axial direction TER 2. During work, the computer controls data acquisition by using the SPIDER 8 by means of specialized software Catman, which has multiple facilities on determining the number of channels, frequency of data acquisition, storing them in formats that allow the processing with specialized programs, etc. Results of the experimental analysis by resistive tensometry are summarized in the graphs in **Figures 9** and **10**.

Processing of the experimental results was performed as follows: Mechanical tensions were measured in the circumferential direction $\sigma_{\theta ij}$ and axial direction σ_{zij}, using known formulas [24]:

$$\sigma_{\theta ij} = \frac{E}{1-\mu^2}(\varepsilon_{\theta i} + \mu\varepsilon_{zj}) \tag{11}$$

$$\sigma_{zij} = \frac{E}{1-\mu^2}(\varepsilon_{zj} + \mu\varepsilon_{\theta i}) \tag{12}$$

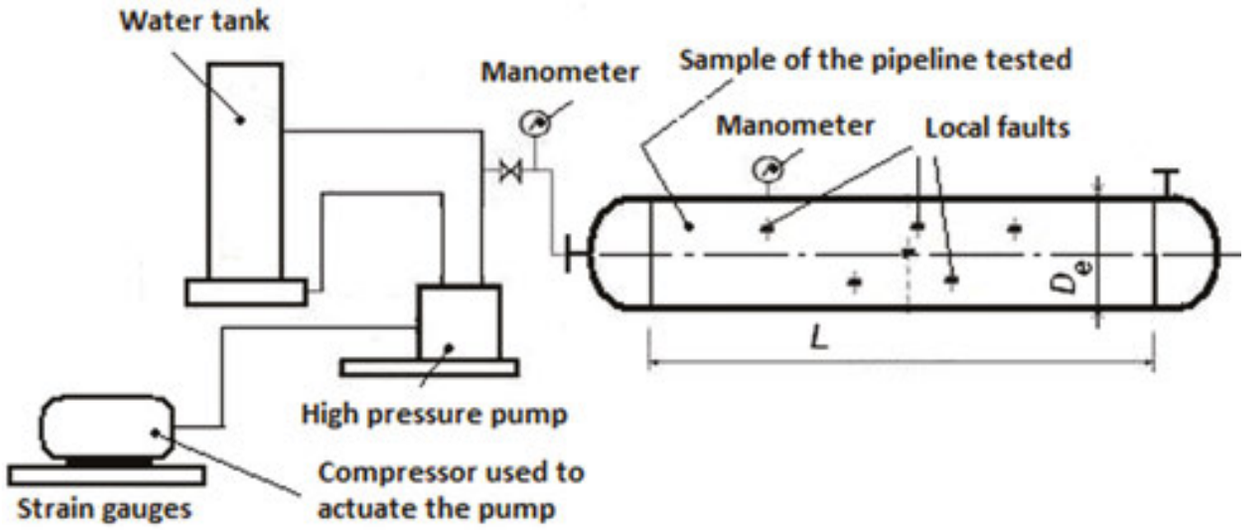

Figure 7. Sketch of the stand used to inner pressure test of pipe samples with local surface defects type loss of material.

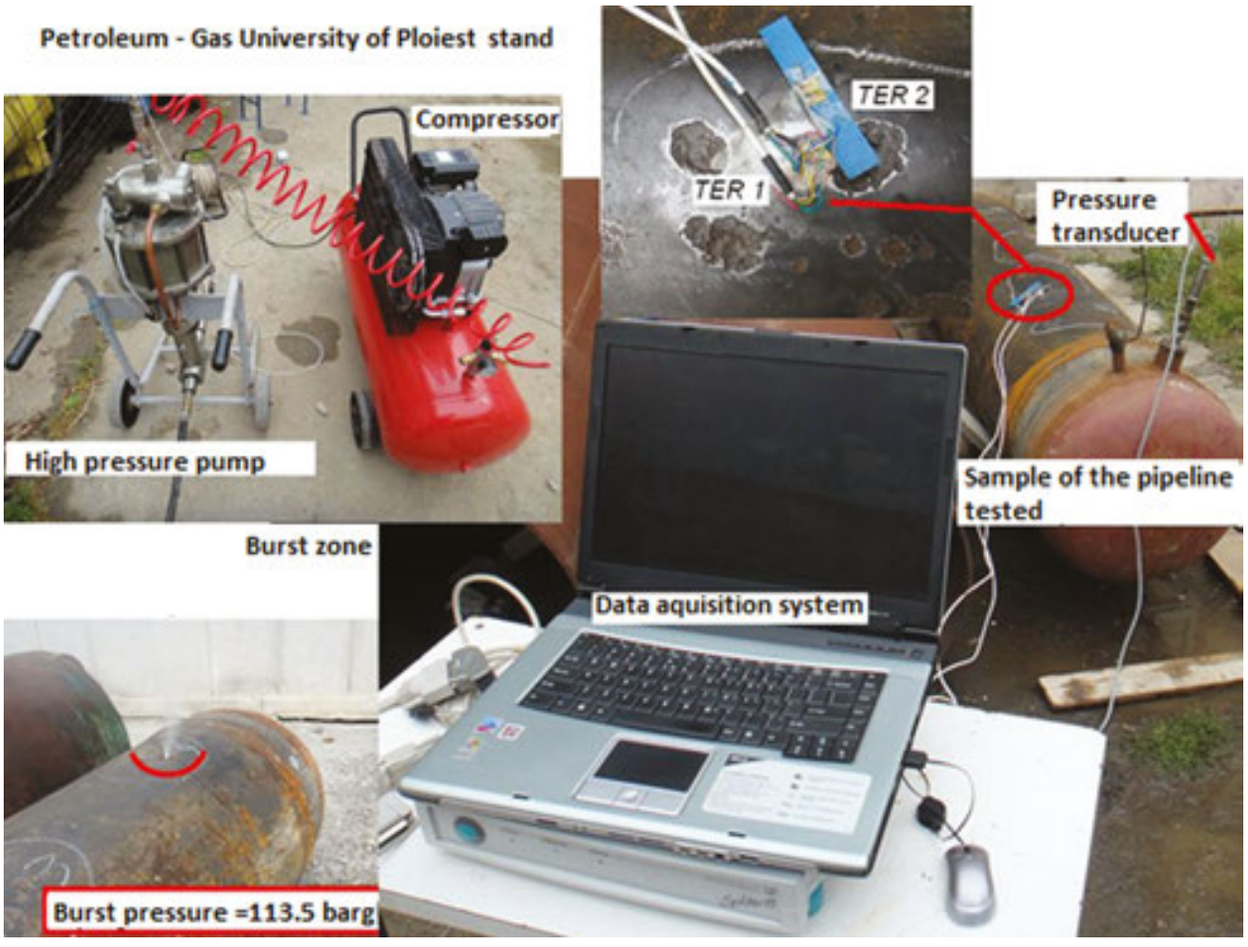

Figure 8. Main components of the stand used to inner pressure test of pipe samples.

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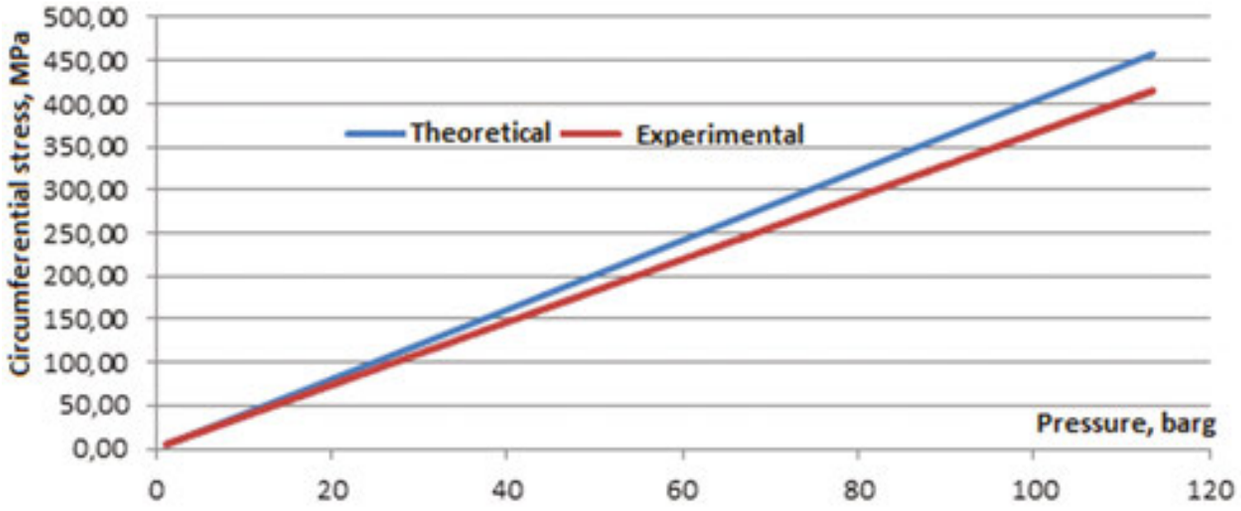

Figure 9. The results of experimental analysis (method of resistive tensometry) for sample with defects type material loss: circumferential stress.

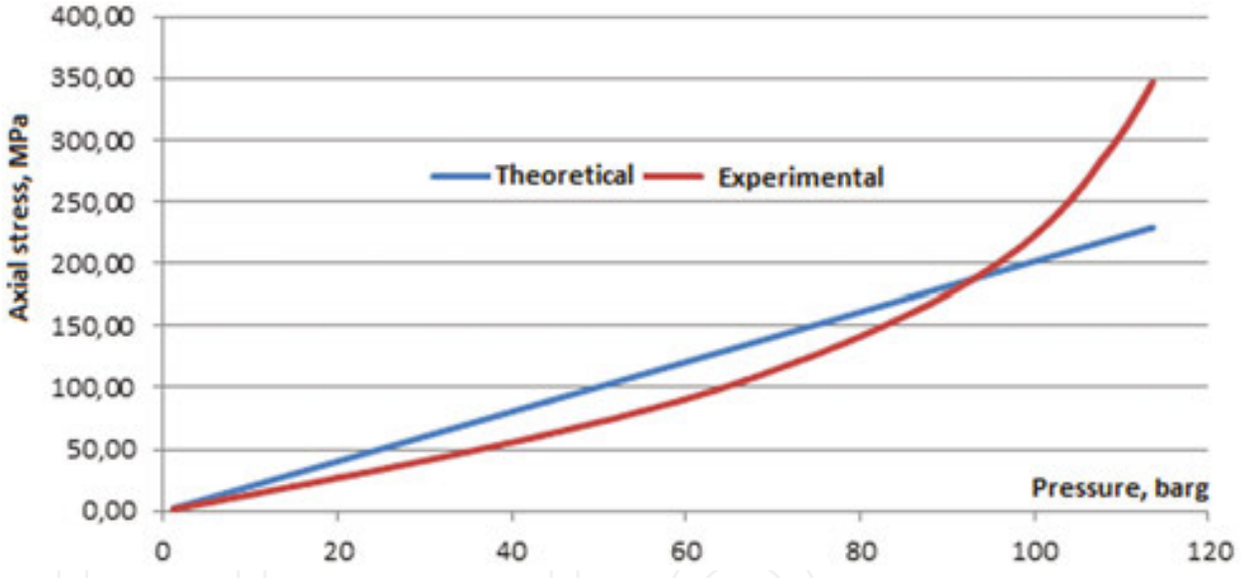

Figure 10. The results of experimental analysis (method of resistive tensometry) for sample with defects type material loss: axial stress.

where E is the longitudinal modulus of elasticity and μ is Poisson's ratio for steel sample; $\varepsilon_{\theta i}$ is specific deformation in the circumferential direction; ε_{zj} is specific deformation in the axial direction (i and j are the identification numbers of transducers). It have been built experimental dependencies of the circumferential and axial deformations shown in **Figure 9**, respectively, **Figure 10**, and these dependencies were compared with the theoretical ones σ_θ, σ_z as described by the formulas:

$$\sigma_\theta = \frac{p_p \cdot D_e}{2t} \tag{13}$$

$$\sigma_z = \frac{p_p \cdot D_e}{4t} \tag{14}$$

In conclusion, experimental verification of the behavior of the mechanical elements of pipeline sets the level of confidence to be associated with the results of assessing the seriousness of defects by analytical methods; the stand designed and built at the Petroleum—Gas University of Ploiesti allows research concerning the pipes behavior with or without defects and can provide results obtained using electro transducers—strain gauges applied to the sample and the sample burst pressure.

3. Conclusions on the case studies

As mentioned in Section 2.1, the case study presented it is focused on practical aspects for the maintenance of pipeline systems. Total length of the pipelines in Romania national gas transport system is 14,500 km and for liquid petroleum products 6000 km. These pipes have a lifetime of between 8 and 45 years, and most of the pipelines have been installed before year 2000. Therefore, the transporters have a real problem with the defects that have appeared over time. Solving them in economic conditions is a difficult problem for these companies. Valorization of PIG inspection results in economic conditions involves selecting of defects. The studies and collaborations of authors with the national companies Transgaz SA and Conpet SA led to implementing maintenance programs (based on the foregoing ideas) that involved the reduction of expenses. Faults evaluation was based on the pressure at the defect position, which reduced the degree of conservatism and maintenance costs. We can do that because we know the position of the defect. The authors of this paper are also working with NRAE from Romania organization dealing with energy issues in Romania. We propose to be added to the indicators that relate to the safety of hydrocarbon transport systems, the probability of failure (with relation from 2.2, an example is introduced in 2.3). This indicator compared to the number recorded accidents through inspections, the number of accidents reported by third parties, the number of accidents that occurred on km of pipe, is a prediction, helping to increase security in transport systems. A procedure was made and submitted for discussion. The role of the experiment in certifying the results and building the trust of the beneficiaries (TSOs) s. 2.4 is underlined by describing the stand used for testing samples of pipeline sections.

Currently, technique for determining the image of defects in the pipelines achieved results increasingly better [25, 26]. On the basis of tridimensional images of the defects can make the three types of analysis described in the introductory part.

The analyzes use only defect length and depth of the defect (level 1); critical profile of the defect in the longitudinal and transverse direction (level 2) **Figure 11a** and **b**; a tridimensional image of the defect generated based on readings during inspection stage, transformed into a solid object and subjected to finite element analysis (level 3) **Figure 11c–e**. Based on the defect report (**Table 1**), we can achieve a three-dimensional model, using a mesh (**Figure 11c**) and the analyze with finite element method (**Figure 11d**). In **Figure 11**, **e** is a detail with defect zone.

The technique described in this case study uses also other features representing the variation of parameters of evaluation: material characteristics; the initial thickness of the pipe; operating pressure. The main objective is to intervene in economic conditions to repair a defect that evolves over time.

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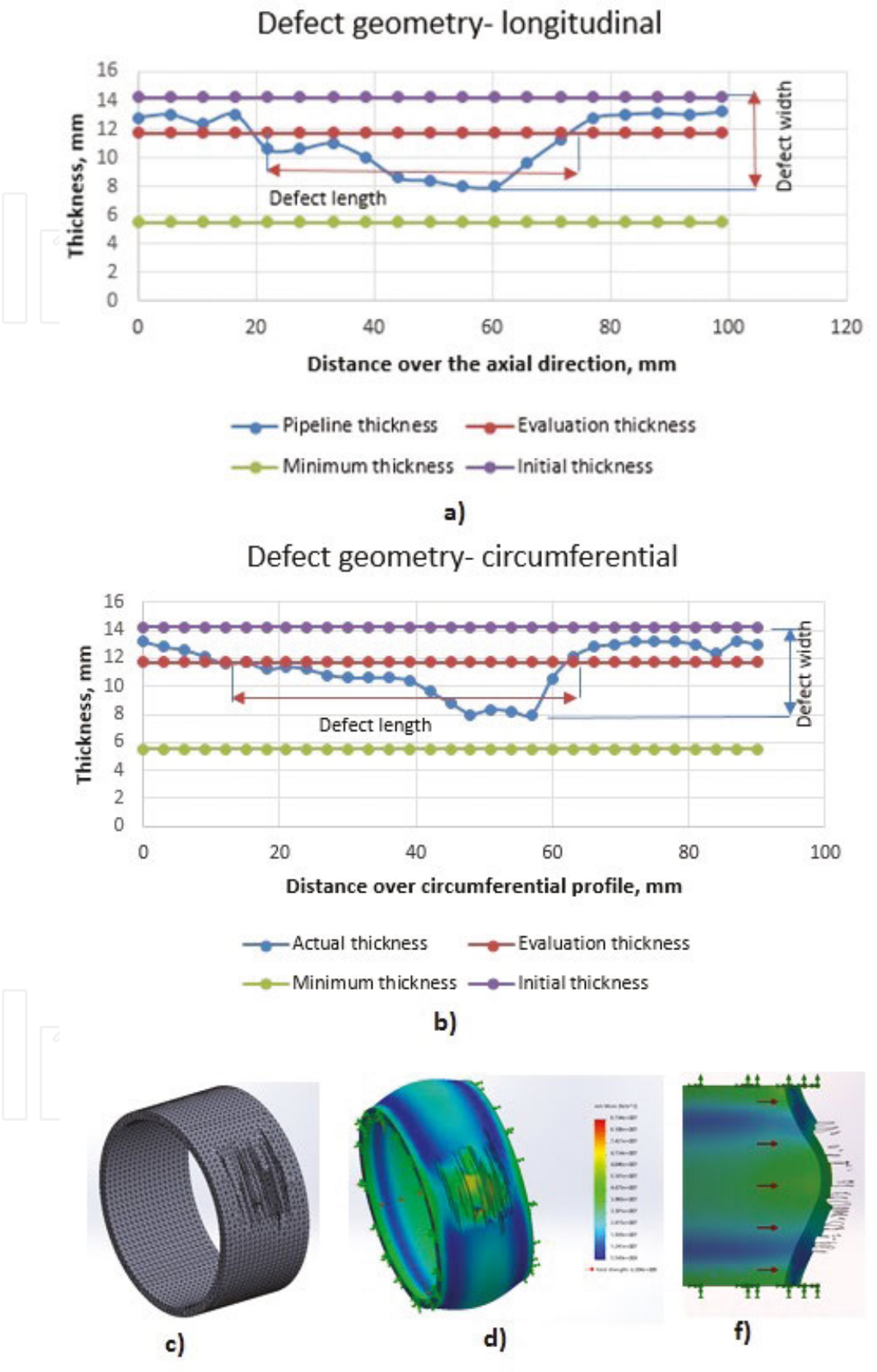

Figure 11. Using different levels of analysis: (a) critical axial profile used in a Level 2 analysis; (b) critical circumferential profile used in a Level 2 analysis; (c) treedimensioal model and the mesh of finite elements for a Level 3 analysis; (d) simulation model (solidworks simulation); a detail with the defect zone.

The truth is that we do not know very well the moment. There are many influences including corrosion rate, an important parameter with a variation difficult to estimate. If we compare with a real-life situation in which political decisions (which are based in many cases on less knowledge) can affect the lives of millions of people, we are still much better.

We know the shape and location of the fault. Finite element analysis seems to be the best method of assessment and perhaps soon a probabilistic assessment, showing that the three-dimensional shape change of the defect in time will be possible. Therefore, the precision regarding of best time for intervention into the system, to avoid a critical situation, it will be increased.

In conclusion, we consider that the main contribution of the article is to transform ideas, indications of standards and inspection data in a coherent system to prevent critical situations, in economic conditions.

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References

[1] Dinu F. Extraction and Processing of Natural Gas. 2nd ed. Romania, Ploiesti: Petroleum and Gas University Publishing House; 2013. p. 352

[2] API 579-1/ASME FFS-1 2007 Fitness-For-Service. Washington, D.C: American Petroleum Institute; 2007.

[3] API 579-1/ASME FFS-1 2009 Example Problem Manual. Washington, D.C.: American Petroleum Institute; 2009.

[4] B31G / ASME 2012 Manual for Determining the Remaining Strength of Corroded Pipelines. USA: American Society of Mechanical Engineers; 2012. p. 60

[5] Shekari E, Khan F, Ahmed S. A predictive approach to fitness-for-service assessment of pitting corrosion. InternationalJournal of Pressure Vessels and Piping. 2016;**137**:13–21

[6] Scano L. Fitness-for-service assessment of a steam pipeline operating in the creep range after 230000 hours of service. In: Proceedings of ASME 2012 Pressure Vessels and Piping Conference, Vol 3: Design and Analysis; 15–19 July; Toronto, Ontario, Canada. 2012. pp. 626–632

[7] Almeida JIL, Rodrigues MC, Mishina KDV. Modeling and level 3 fitness-for-service assessment of a cylindrical pressure vessel with general metal loss in conjunction with the numerical thermal transient analysis. InternationalJournal of Mechanics and Applications. 2014;**4**:80–93. DOI: 10.5923/j.mechanics.20140403.02

[8] Janelle JL. An overview and validation of the fitness-for-service assessment procedures for local thin areas[thesis].Akron, Ohio, United States: University of Akron; December, 2005.

[9] Adib-Ramezani H, Jeong J, Pluvinage G. Structural integrity evaluation of X52 gas pipes subjected to external corrosion defects using the SINTAP procedure. International Journal of Pressure Vessels and Piping. 2006;**83**:420–432

[10] Ahammed M. Prediction of remaining strength of corroded pressurized pipelines. InternationalJournal of Pressure Vessels and Piping. 1997;**71**:213–217

[11] Ahammed M. Prediction of remaining strength of corroded pressurized pipelines. International Journal of Pressure Vessels and Piping. 1998;**75**:321–329

[12] Li SX, Yu SR, Zeng HL, Liang R. Predicting corrosion remaining life of the underground pipelines with mechanically based probabilistic model. Journal of Petroleum Science and Engineering. 2009;**65**:162–166

[13] Netto TA, Ferraz US, Estefen SF. The effect of corrosion defects on the burst pressure of pipelines. Journal of Constructional Steel Research. 2005;**61**:1185–1204

[14] Teixeira AP, Soaresa CG, Nettob TA, Estefen SF. Reliability of pipelines with corrosion defects. International Journal of Pressure Vessels and Piping. 2008;**85**:228–237

[15] Minescu M, Pana I. The equivalence of the assessments procedures API 579 and ASME B31G. Petroleum and Gas Bulletin Technical Series. 2012;**64**:11–20

[16] DNV-RP-G101 2010 Recommended Practice Risk Based Inspection of Offshore Topsides Static Mechanical Equipment. Det Norske Veritas. October 2010. Available from: http://www.dnv.com [Accessed: 2016]

[17] Dinu F. Extraction and Treating of Natural Gas, 1st ed. Romania, Ploiesti: Petroleum and Gas University Publishing House; 2009. p. 256

[18] Caleyo F, Gonzales JL, Hallen JM. A study of the reliability assessment methodology for pipelines with active corrosion defects. International Journal of Pressure Vessels and Piping. 2002;**79**:77–86

[19] De Leon D, Macias OF. Effect of spatial correlation on the failure probability of pipelines under corrosion. International Journal of Pressure Vessels and Piping. 2005;**82**:123–128

[20] Mustaffa Z, Gelder P. A review and probabilistic analysis of limit state functions of corroded pipelines. In: Proceedings of the Twentieth International Offshore and Polar Engineering Conference; 20–25 June; China, Beijing. 2010. pp. 626–632

[21] Zecheru G, Neacsu M, Lata I. The probabilistic conception of the pipeline defect acceptance charts. Fracture Mechanics Bulletin ARMR. 2005;**17**:31–36

[22] Minescu M, Pana I. Safety evaluation of the pipelines systems for petroleum products. Applied Mechanics and Materials. 2013;**371**:782–786. DOI:10.4028/www.scientific.net/AMM.371.782

[23] Minescu M, Pana I, Dumitrescu A. Implementation of an Assessment Procedure Type Fitness-For-Service in Accordance with API Standard 579, for Oil Pipelines Faults and Technical Assessment of a Real Pipeline Section [research service contract no. 387/09.12.2010, beneficiary S.C. Conpet SA Romania], Petroleum & Gas University Ploiesti; 2011

[24] Stanciu LS, Popa I. Practical Works and Calculation for Mechanical Vibration. 1st ed. Romania, Ploiesti: Petroleum Gas University Publishing House; 2015. p. 200

[25] Barbian A, Beller M, Hugger A, Jäger C, Pfanger A. Threshold, accuracies, and Resolution, Proceedings of the Pipeline Pigging and integrity Conference; 15–18 February; Houston, Clarion, 2010

[26] Barbian A, Beller M, Hartmann S., Schneider U. High resolution ultrasonic in-line inspection: Added value and special applications. 6th Pipeline Technology Conference; 4 April; Hannover. Germany, Hannover Messe, 2011