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## **PREDICTIVE MAINTENANCE OF PIPELINES WITH DIFFERENT TYPES OF DEFECTS**

**Abstract.** The paper describes a tested and proven practical methodology of predictive maintenance of pipelines with two types of defects—«loss of metal» and «pipe wall lamination», detected by the ILI technology.

For the defects of the «pipe wall lamination» type the assessment of their level of danger is conducted only after they are converted to surface «loss of metal» type defects. The paper presents models on how to adequately convert the «pipe wall lamination» type of defects to the «loss of metal» type defects.

A methodology is described on how to rank the defects according to their level of danger (with respect to the rupture type of failure), and how to perform the probabilistic assessment of the residual life of the inspected pipeline. The defects detected by the ILI are divided, depending on their type, size, and the level of safety factor, into three following categories: Dangerous, Potentially dangerous and Not dangerous defects.

In order to account for «leak» and «rupture» types of failure, a computer based express assessment is developed of the level of severity of each defect. This defect assessment is based on graphs, which restrict the permissible sizes of defects and allow making operative decisions as to which maintenance measures should be taken, regarding each detected defect and the pipeline segment as a whole. The pipeline defects are ranked according to their potential danger, which depends on their location on the graphs. These graphs form five zones, which define the level of the defects danger.

The probabilistic assessment of the residual pipeline life is performed taking into account the stochastic nature of defect growth. In order to achieve this, the maximal  $\gamma$ -percentile corrosion rate is defined over all detected defects. The distribution of the  $n$  detected pipeline defects is described by the two-parameter Weibull probability density function (PDF). As the main decision parameter the gamma-percent operating time is chosen. It is characterized by 1) the safe operating time, and 2) the percentile probability that during this time the pipeline limit state will not be reached.

A detailed example of implementation of the described methodology to a real product pipeline segment operating in a severe corrosion environment is given. The economical effect of the implementation is outlined.

**Keywords:** Pipelines, Defects, Maintenance, Gamma-percent operating time.

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## ПРОГНОЗНОЕ ОБСЛУЖИВАНИЕ ТРУБОПРОВОДОВ С РАЗЛИЧНЫМИ ТИПАМИ ДЕФЕКТОВ

**Аннотация.** В статье описана протестированная и проверенная практическая методика предсказательного мейтенанса трубопроводов с двумя типами дефектов – «потеря металла» и «расслоение стенки трубы», обнаруженных в результате внутритрубной диагностики (ВТД).

Для дефектов типа «расслоение стенки трубы» оценка уровня опасности проводится только после того, как они преобразуются в дефекты типа «потеря металла». В статье представлены модели того, как адекватно преобразовывать дефекты типа «расслоение стенки трубы» в дефекты типа «потеря металла».

Описывается методология ранжирования дефектов в зависимости от их уровня опасности (в отношении типа разрушения) и метод определения вероятностной оценки остаточного ресурса проинспектированного трубопровода. Дефекты, обнаруженные при ВТД, в зависимости от их типа, размера и уровня опасности подразделяются на три следующие категории: опасные, потенциально опасные и не опасные.

Чтобы учесть отказ типа «течь» и «разрыв», разработана экспресс-оценка на основе уровня опасности каждого дефекта. Эта оценка дефектов основана на графиках, которые ограничивают допустимые размеры дефектов и позволяют принимать оперативные решения относительно того, какие меры по техническому обслуживанию следует принимать в отношении каждого обнаруженного дефекта и сегмента трубопровода в целом. Дефекты трубопровода оцениваются в соответствии с их потенциальной опасностью, которая зависит от их местоположения на графиках. Эти графики образуют пять зон, которые определяют уровень опасности дефектов.

Вероятностная оценка остаточного ресурса трубопровода выполняется с учетом стохастической природы роста дефектов. Для этого по всем обнаруженным дефектам определяется максимальная  $\gamma$ -процентная скорость коррозии. Распределение  $n$  обнаруженных дефектов трубопровода описывается двухпараметрической функцией плотности вероятности Вейбулла (PDF). В качестве основного параметра выбирается остаточный гамма-процентный ресурс. Он характеризуется 1) безопасным временем работы и 2) вероятностью (перцентиль), что за это время предельное состояние трубопровода не будет достигнуто.

Дается подробный пример реализации описанной методологии для реального сегмента трубопровода, работающего в условиях коррозии. Описан экономический эффект от реализации.

**Ключевые слова:** Трубопроводы, Дефекты, Техническое обслуживание, Гамма-процентный остаточный ресурс.

### 1. Introduction

All the defects detected by the ILI are divided, depending on their type, size, and the level of safety factor, into three following categories: *dangerous*; *potentially dangerous* and *not dangerous defects*.

*Dangerous defects* require immediate or ASAP repair. Dangerous defects are the local surface defects which depth is greater than 60% of pipe wall

thickness for pipelines transporting corrosive products, and 80% of pipe wall thickness for pipelines transporting non corrosive products.

*Potentially dangerous defects* with sizes larger than the ultimate permissible sizes, as prescribed by international codes (IC), but smaller than the sizes of dangerous defects. These defects require DA and should be repaired according to the IMP.

*Not dangerous defects* do not decrease the bearing capacity of the pipeline, and don't imply DA or repair. These defects include surface anomalies of pipe metal, permitted by the requirements of IC, as well as internal metallurgical defects.

## 2. Ranking of defects on the level of danger with respect to the rupture type of failure

The strength safety factor of a defective section of a pipeline with respect to the rupture type of failure is defined as:

$$N_1 = P_f / P_{op}$$

where  $P_f$  is the failure pressure estimated by some code, e.g. B31G [1], modified B31G (B31Gmod) [2], DNV [3], PCORRC (Battelle) [4] or Shell92 [5];  $P_{op}$  is the operating pressure.

The potential danger of the defective section of a pipeline is estimated with the strength safety factor using the following conditions [6, 7]:

- for dangerous defects:  $N_1 \leq k_1 \cdot N_2 + k_2$ ;
- for potentially dangerous defects:

$$k_1 \cdot N_2 + k_2 < N_1 < N_2 \quad (1)$$

- for not dangerous defects:  $N_1 \geq N_2$ ,

Where coefficients  $k_1 = 0.7$ ,  $k_2 = 0.3$  for pipelines transporting non-corrosive products;  $k_1 = 0.6$ ,  $k_2 = 0.4$  for pipelines transporting corrosive products (such as gas containing sulfur hydrogen);  $N_2$  is the allowed safety factor, determined by formula:

$$N_2 = \sigma_s / [\sigma], \quad [\sigma] = SMYS / n_k,$$

Where SMYS is the specified minimum yield stress;  $n_k$  is safety factor for allowed stresses;  $\sigma_s$  is the flow stress which is calculated depending on the used code. For example, B31G [1], B31Gmod [2], Shell92 [5] and DNV [3] codes for assessing the residual strength of defective cross sections with longitudinally oriented defects are based on the equation of plastic fracture criterion, which has the form [8]:

$$\sigma_f = \sigma_s \frac{(A_0 - A)}{(A_0 - AM^{-1})} \quad (2)$$

where  $\sigma_f$  is the hoop stress at failure of the defective cross section of a pipeline;  $A_0$  is the initial area of the longitudinal cross section of the defective site of a pipeline,  $A_0 = l \cdot wt$ , where  $l$  is the maximum defect length along the pipe axis,

$wt$  is the pipe wall thickness;  $A$  is the defect area in the longitudinal direction of a defective section of a pipeline,  $A = k_s \cdot l \cdot d$ , where  $d$  is the maximum defect depth,  $k_f$  is the coefficient of the defect shape (e.g. for B31Gmod  $k_f = 0.85$ );  $M$  is the Folias factor.

Thus, according to the B31G code [1],  $\sigma_s = 1.1SMYS$ , for B31Gmod [2]  $\sigma_s = SMYS + 68.95MPa$  (10ksi).

Note, that the level of danger of a defect, defined by conditions (1), considers only the rupture type scenario of pipeline failure.

Maximum allowable operating pressure (MAOP) of the defective cross-section of a pipeline can be calculated using the safety factor, by formula:

$$P_a = P_f / N_2 \tag{3}$$

**3. Express assessment of the level of danger of the pipeline defective cross-sections**

In order to account for both «leak» and «rupture» types of failure, graphs should be constructed, which restrict the permissible sizes of defects and allow making operative decisions as to which maintenance and operational measures should be taken, as well as allow ranking of defects according to the level of danger they present, depending on their location on the graphs (see Figure 1).

*Line I* is the boundary for *Zone I* which is comprised of pipeline design operational conditions, and allowance for corrosion (10% or 20%  $wt$ ).

*Line II* is produced by step-by-step calculations of MAOP using formula (3) up to the value of OP (as designed or planned) for a pipeline by changing the length and depth of the defect in formula (2), respectively, in 1 mm and 0.05 mm increments. In this case, the pipeline operating pressure is allowed with a design safety factor of  $N_1 = N_2$ , as related to failure pressure.

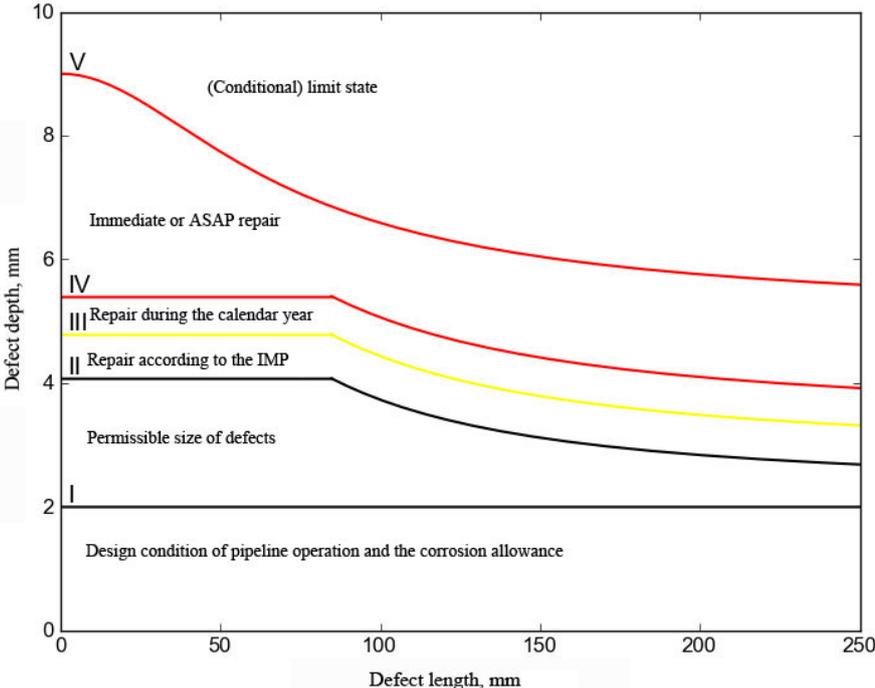


Figure 1. Graphical representation of zones of the parameters of defects with varying levels of their potential danger (for pipeline with  $wt = 9$  mm)

*Line III* is produced by step-by-step calculations of MAOP for the defective section of the pipeline, up to a value at which the failure pressure is  $N_1 = [0,8 \cdot N_2 + 0,2]$  times more than the OP of a pipeline, by incrementally changing, correspondingly, the length and depth of the defect in formula (2).

*Line IV* is produced by step-by-step calculations of MAOP, up to the value of OP, by changing the length and depth of the defect in formula (2), and utilizing the safety factor  $N_1$ , which restricts the limit sizes of the potentially dangerous defects.

*Line V* is produced by step-by-step calculations of the failure pressure  $P_f$ , up to the value of OP, while changing the length and depth of the defect in formula (2); i.e., determine the defect size which can cause pipeline failure at the OP and  $N_1 = 1$ .

The horizontal zones, which restrict the limit depth of defects, are produced by carrying over the point from Line IV (correspond to 60 % or 80 % of pipe wall thickness) to the Lines II and III.

Depending on the location of ILI data on the graphs, the conditions of further pipeline operation or repair of defective cross sections are determined:

- *Zone # 1* contains the corrosion allowance and the design permitted conditions of the pipeline;
- *Zone # 2* contains permissible size of defects for the case when pipeline is operated under “normal” conditions, which provide for effective electrochemical and inhibitor protection;
- *Zone # 3* contains potentially dangerous defects. Defect should be repaired according to the integrity maintenance plan (IMP), if the defect is below the yellow Line III, and during the calendar year, if the defect is above the yellow Line III;
- *Zone # 4* contains dangerous defects, which should be repaired immediately or ASAP;
- *Zone #5* is the conditional failure area depending on the used design code (pipeline limit state).
- Unlike the assessment of the level of danger of defects defined in conditions (1), this express assessment of residual strength of the defective cross section accounts for the «leak» as well as for the «rupture» type of failure.

#### **4. Models of converting the «pipe wall lamination» type defects to the surface «loss of metal» type defects**

The laminations are caused by the steel production and pipe manufacturing technology, and may also appear during pipeline operation. According to [6, 7] the laminations can be further classified as metallurgical laminations, hydrogen induced cracking (HIC), non-metallic inclusions, roll-ins, and such.

Models of converting [6, 7] of the laminations to the surface «*loss of metal*» type defects, and calculating the thickness of the converted defect layer

of pipe metal, for the *not-so-long* laminations, when the defect length is less or equal to the 0.2 pipe diameter ( $l \leq 0.2D$ ), are shown in Fig. 2, where  $d$  is the thickness of detected lamination,  $d^*$  is the thickness of the converted defect (further it is used as actual defect depth),  $l$  is the length of lamination along the pipe longitudinal axis,  $wt$  is the pipe wall thickness,  $wt_r$  is the residual pipe wall thickness.

According to Fig. 2, for all cases, except one (see last case of Fig. 2), the converted thickness of lamination is equal to the detected lamination, which means that in this case *conversion is not required*.

For *long* laminations ( $l > 0.2D$ ), which are not exiting to the surface of the pipe wall, the depth of converted defect layer is equal to the greatest thickness of lamination in the circumferential direction of the pipe, plus half the thickness of lamination along the pipe longitudinal axis:

$$d^* = d_l + 0.5d_a \quad (4)$$

where  $d_a$  is the thickness of lamination along the longitudinal pipe axis;  $d_l$  is the thickness of lamination in the circumferential direction of the pipe.

For *long* laminations ( $l > 0.2D$ ) which exit on the inner surface of the pipe wall, the exit being of size  $l_a$  along the pipe longitudinal axis (*and the product being pumped penetrates the pipe wall*), the failure pressure is calculated based on the thickness of the lamination along the pipe longitudinal axis, and its length in the pipe circumferential direction. The metal of the inner surface of the pipe, and the defect-free metal layer are carrying the pressure load. The smaller the lamination length around the pipe circle, the more pressure is carried by the inner layer of the pipe wall metal. Upon reaching by the lamination the size of pipeline diameter along pipe circumference, significant bending moments are created in the inner layer of pipe wall metal, and its capacity to hold the pressure is significantly reduced. For *long* laminations the depth of converted defect layer is calculated by formula:

$$d^* = d_l + d_a - 0.5d_a \left(1 - \frac{l_a}{l}\right) \left(1 - \frac{l_\varphi}{l}\right), \quad l_\varphi < D$$

$$d^* = d_l + d_a, \quad l_\varphi \geq D$$

where  $l_\varphi$  is the length of lamination along the pipe circumference.

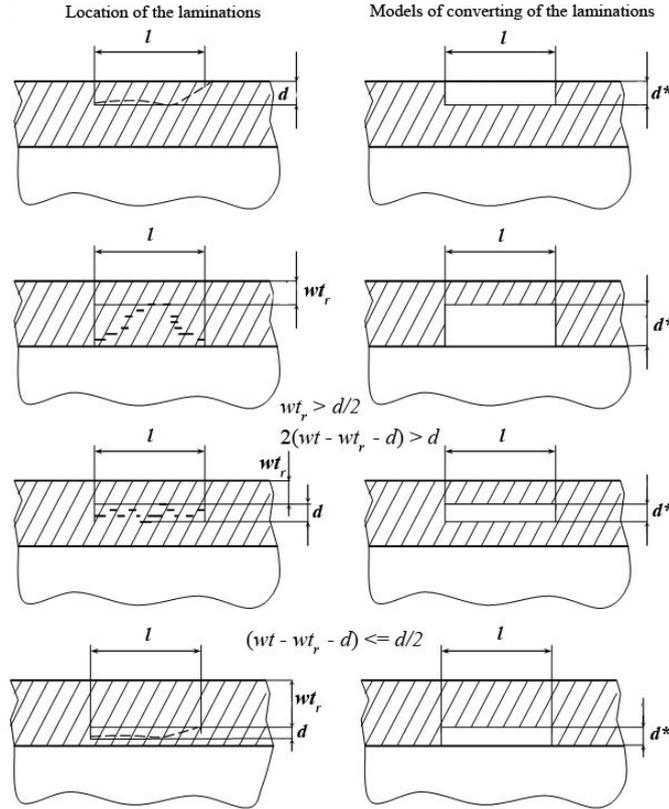


Figure 2. Location of the laminations and models of its converting to the surface «loss of metal» type defects

If a *long* lamination ( $l > 0.2D$ ) is exiting to the outer surface of the pipe wall thickness on length  $l_a$  along the pipe longitudinal axis (*and the product does not penetrate the pipe wall*), the failure pressure is calculated based only on the thickness (depth) of the lamination. Metal of the outer surface of the pipe wall is carrying a part of the pressure load, together with the defect-free metal layer. In this case, the depth of the converted defect layer is calculated by the formula:

$$d^* = d_l + d_a - 0.5d_a \left( 1 - \frac{l_a}{l} \right) \quad (5)$$

For pipelines transporting non-corrosive products, the lamination length  $l_\varphi$  and depth  $d_l$  over the pipe circumference, which exits to the inner surface of the pipe wall, are limited by following inequalities:

$$\begin{aligned} d_l &\leq 0.4wt \\ 0.4wt &\leq d_l \leq 0.6wt \end{aligned} \quad (6)$$

In the first case of formula (6) the length  $l_\varphi$  should not exceed 1/3 of pipe circumference length; in the second case the  $l_\varphi$  should not exceed 1/6 of pipe circumference length.

For pipelines transporting corrosive products (containing sulphur hydrogen), the lamination length  $l_\varphi$  and thickness  $d_l$  along the pipe

circumference, which exit to the surface of the pipe wall, are limited by following inequalities:

$$\begin{aligned} d_l &\leq 0.2wt \\ 0.2wt &\leq d_l \leq 0.4wt \end{aligned} \quad (7)$$

In the first case of formula (7) the length  $l_\varphi$  should not exceed 1/6 of pipe circumference length; in the second case  $l_\varphi$  should not exceed 1/12 of pipe circumference length.

If there is a defect with signs of HIC, the probability of its opening on the inner surface of the pipe, and damaging a metal layer by a crack up to 1 / 3 of the lamination length, must be accounted for. But even with this, the metal from the inner surface of the pipe and a defect-free metal layer are jointly carrying a part of the pressure load. The smaller the length of lamination along pipe circumference, the more load is imposed on the inner layer of metal of pipe wall. When the length of a lamination along pipe circumference becomes half the pipeline diameter, significant bending moments in the inner layer of metal are created, and the pipe bearing capacity is significantly reduced. In this case, the depth of the converted defect layer is calculated by the formula:

$$\begin{aligned} d^* &= d + (wt - wt_r - d) \left( 0.3 + 1.4 \frac{l_\varphi}{D} \right), l_\varphi < D / 2 \\ d^* &= d + wt_r, l_\varphi \geq D / 2 \end{aligned}$$

The defects of «pipe wall lamination» type, after being converted to the «wall thinning» type defects, are treated as “loss of metal” type defects, when assessing the level of their danger.

**Example.** Consider two defects of the «pipe wall lamination» type, which parameters are listed in Table 1.

Convert the defects of «pipe wall lamination» type to the surface «loss of metal» type defects. Both defects are *long* (as their length along the pipe axis is being greater than  $0.2D = 65\text{ mm}$ ).

For the first defect, which does not exit to the surface of the pipe, calculate the converted depth using formula (4), and assuming that the maximum thickness of the damage along the pipe axis is equal to the thickness of the damage along the pipe circumference:

$$d^* = d_l + 0.5d_a = 2.25 + 0.50 \cdot 2.25 = 3.38\text{ mm}$$

For the second defect use the formula (5):

$$d^* = d_l + d_a - 0.5d_a \left( 1 - \frac{l_a}{l} \right) = 1.80 + 1.80 - \frac{1.80}{2} \left( 1 - \frac{22.00}{99.00} \right) = 4.29\text{ mm.}$$

Thus, after converting defects of the «pipe wall lamination» type they are considered as surface defects of the «loss of metal» type.

Table 1

**Parameters of the «pipe wall lamination» type defects**

#	Type of defect	Lamination thickness $d_a$ , mm	Length $l$ of lamination along pipe longitudinal axis, mm	Lamination exit length $l_a$ on pipe surface, mm
1	Lamination	2.25	224.00	-
2	Lamination exiting to the pipe wall surface	1.80	99.00	22

### 5. Assessing the conditional maximum growth rate of defects with given probability

In real life corrosion rates (CRs) are random variables (RVs). Realizing this fact, some pipeline operators utilize the following method of forecasting the future state of the pipeline, based on predicting the *maximal possible* CR. When assessing the maximal possible rate of defect growth it is assumed that the probability density function (PDF) of the depths of the  $n$  defects, which are actually present in the pipeline transporting oil or gas condensate substances, is, as a rule, described by the Weibull law. The two-parameter Weibull IDF has the form:

$$F(d) = 1 - e^{-(d/\alpha)^b}$$

where  $d$  is the defect depth,  $\alpha$  and  $b$  are the IDF parameters.

The maximal defect depth, which is possessed or exceeded by the  $(1 - \gamma)$  portion of the total number of defects found during the ILI, is defined according to following formula (expression for the Weibull PDF quantile):

$$d_{\max \gamma} = \alpha \cdot (-\ln(1 - \gamma))^{1/b} \quad (8)$$

In the case when the distribution of the defect set is normal or approximately normal, the depth of the defect with probability  $\gamma$  is assessed using the formula for the quantile of the normal distribution:

$$d_{\max \gamma} = \Phi(\gamma) \sigma_d + \bar{d} \quad (9)$$

where  $\Phi(\gamma)$  is the inverse of the standard normal CDF,  $\bar{d}$  is the sample average of the defects depth,  $\sigma_d$  is the sample standard deviation of the defects depth,  $n$  is the number of defects present in the pipeline.

If results of two sequential ILIs are available, the maximal CR, with probability of  $\gamma$ , is defined by formula:

$$a_{\max \gamma} = \frac{d_{\max \gamma L} - d_{\max \gamma P}}{t_L - t_P} \quad (10)$$

Here  $d_{\max \gamma P}, d_{\max \gamma L}$  are the maximal depths of the defects as defined by formula (8) or (9), for the previous (P) and the last (L) ILI correspondingly.

If results of only one ILI are available, then the maximal, with probability  $\gamma$ , CR is defined according formula:

$$a_{\max\gamma} = \frac{d_{\max\gamma}}{\tau_d} \quad (11)$$

where  $\tau_d$  is the net time of pipeline operation before the time of conducting the ILI (years).

The Weibull PDF parameters can be assessed by numerical solution of the following system of equations [9]:

$$\left\{ \begin{array}{l} \alpha = \left( \frac{\sum_{i=1}^n d_i^b}{n} \right)^{\frac{1}{b}} \\ \frac{1}{b} + \frac{1}{n} \sum_{i=1}^n \ln d_i - \frac{\sum_{i=1}^n d_i^b \ln d_i}{\sum_{i=1}^n d_i^b} = 0 \end{array} \right.$$

where  $d_i$  is the depth of  $i$ -th defect,  $n$  is the total number of defects.

For other methods of assessment CRs see [10].

## 6. Assessing the pipeline residual life time

The pipeline longevity indicators are calculated for a given confidential probability  $\gamma$ , using the non-failure criterion. This criterion holds true until the defect reaches the maximum allowable depth  $d_{III}$ , as defined by the Line III of Zone #3 (see Figure 1). According to this approach, the residual life of the  $i$ -th defective cross section of a pipeline is defined by the formula:

$$\tau_i^{rl} = \frac{d_i^{III} - d_i}{a_{\max\gamma}}, \quad i = 1, \dots, n \quad (12)$$

where  $d_i^{III}$  the maximum allowable depth of the  $i$ -th is defect  $d_i$ ;  $a_{\max\gamma}$  is the maximal CR with probability  $\gamma$ , as defined by formula (10) or (11);  $n$  is the total number of defects.

Note that the calculation of the residual life by formula (12) is made for the current length of the defect. Thus, its growth in time is not taken into account.

Then, on the basis of the weakest link principle, the residual life of pipeline is calculated by the formula:

$$\tau_{rl} = \min_{i=1, n} \{ \tau_i^{rl} \}$$

The residual gamma-percent life time, from the last inspection to the time when the most dangerous defect reaches the limit state, is calculated as:

$$\tau_{rl\gamma} = \tau_{rl} \left( 1 - U \frac{V_d}{\sqrt{n}} \right)$$

where  $U$  is the quantile of the normal distribution, depending on the confidence level  $\gamma$ .  $V_d$  is the sample coefficient of variation of the defects.

The date of next ILI should not be greater than the gamma-percent life ( $\tau_{rl\gamma}$ ), *minus* one year.

## 7. Some results of analysis

The analysis was performed for a pipeline section 11 km long with following parameters: outside diameter (D) is 325 mm; pipe wall thickness (wt) is 9 mm; SMYS is 245 MPa; Maximal Operating Pressure ( $P_{op}$ ) is 6.4 MPa.

ILI was carried out in 2005, which resulted in finding 3384 defects of the «loss of metal» type and 11 defects of the «pipe wall lamination» type. A small part of the defects was verified.

In the *first stage* of analysis, using the methodology described in [11, 12] estimates of the true sizes of the depths of the verified and non verified defects were calculated and used in further analysis.

The model comprehensive and consistent methodology described in papers [11, 12] allows for constructing consistent and unbiased assessments of the true immeasurable sizes of defect parameters and their variances for the case when the needed information about the ILI/DA tool and the verification instrument VI are obtained from the field and lab measurements. The presented in these papers method permits assessing the “*in the field*” statistical properties of the measurement errors of ILI/DA technology and of the verification tools (for the case “one measurement by each tool”). Also a method for calibrating the inspection tool is presented, which allows assessment of the true values of defect parameters.

In the *second stage* of analysis, the defects of «pipe wall lamination» type were converted to the surface defects of the «loss of metal» type by the method described above.

The failure pressure is estimated using the B31Gmod code with the different coefficients of defect shape  $k_f$ , (= 0.67 for external defects and =1.0 for internal defects).

In the *third stage* of analysis, the express assessment of the level of danger of the defects was performed, results of which are presented in Figures 3-5.

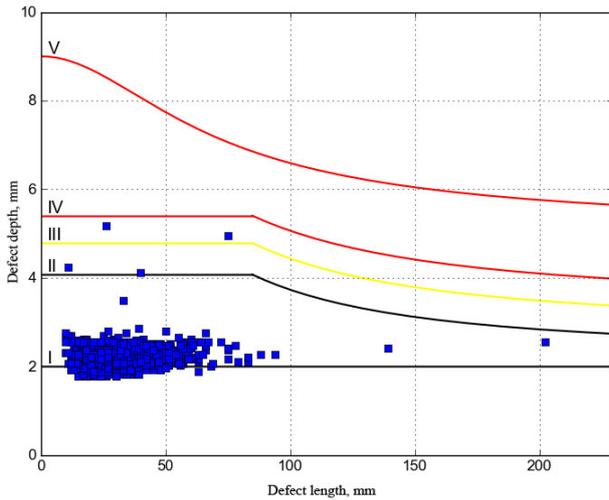


Figure 3. Express assessment of the level of danger of *internal* defects of the «loss of metal» type

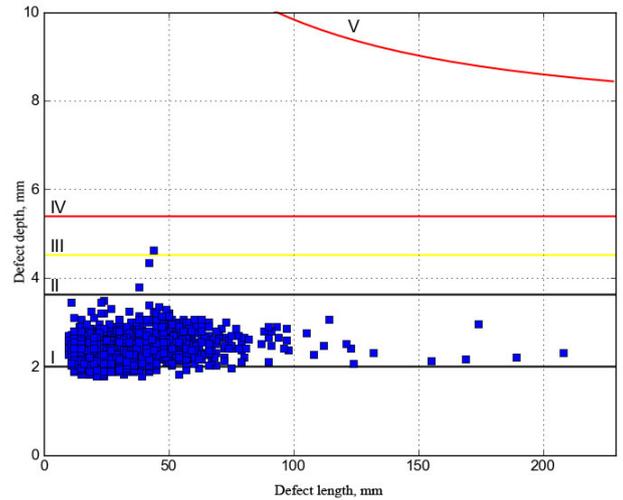


Figure 4. Express assessment of the level of danger of *external* defects of the «loss of metal» type

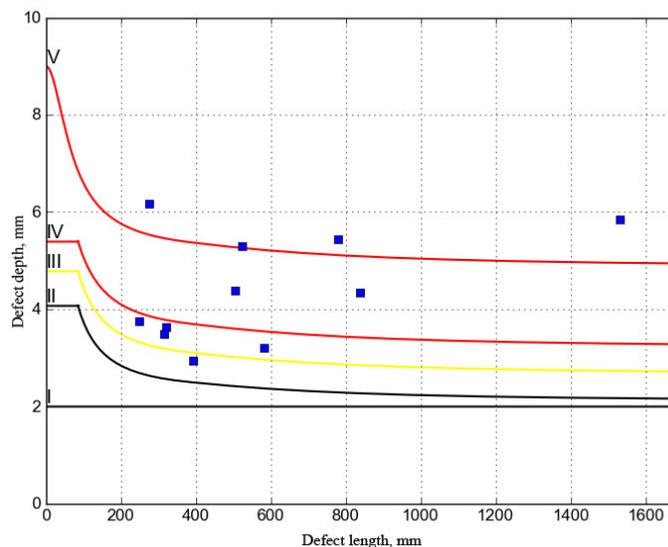


Figure 5. Express assessment of the level of danger of defects of the «pipe wall lamination» type

According to Figs. 3 and 4, three defects of the «loss of metal» type must be repaired within one year after ILI, as these defects are located between Lines III and IV; and four defects located between Lines II and III should be repaired according to the IMP.

According to Fig. 5, six defects of the «pipe wall lamination» type should be repaired ASAP; four defects must be repaired within one year after ILI, as these defects are located between Lines III and IV; and one defect, which is located between the Lines II and III, should be repaired according to the IMP.

In the *fourth stage*, the rates of growth of the length and depth of defects of the «loss of metal» type were found, as they are needed to predict the future sizes of defects parameters and to assess residual life using the method described

above. The calculation was performed using probability  $\gamma = 0.95$ . The pipeline operation time  $\tau_d$  prior to the last ILI is 26 years. According to the conducted analysis, the most appropriate distribution of assessments of the true sizes of defects depths and lengths is normal. The most appropriate distribution of defects parameters can be identified using various goodness-of-fit tests, for example, the chi-square and Kolmogorov-Smirnov tests. Hence, the maximal defect depth and length, which is possessed or exceeded by the  $(1 - \gamma)$ -th portion of the total number of defects found during the ILI, and the maximal CR with the probability  $\gamma = 0.95$ , are equal to the values given in Table 2.

Table 2

**Maximal defect depth and length and the maximal CR, with probability  $\gamma = 0.95$**

Defect Parameters	Maximal CR for defect parameters, <i>mm/year</i>	Maximal size of defect parameters, <i>mm</i>
Depth	0.11	2.72
Length	2.34	60.96

In the *fifth stage*, the residual life of each defect was calculated using formula (12) based on the assessments of CR of defects parameters. The calculation results are presented in Table 3 and Fig. 6. According to the obtained results, the residual life of nine defects is less than 10 years. In Table 3, the defects ##1-3 should be repaired ASAP, defects ## 4-7 - within one year after ILI, and defects ## 8 and 9 - according to the IMP.

Table 3

**Residual life of the defective cross sections of the pipeline (assessments of true sizes of defects depths were used)**

Defect #	Assessment of true size of defect depth, mm	Length, mm	Type of defect	Residual life, years
1	4.95	75	internal	0
2	4.63	44	external	0
3	5.17	26	internal	0
4	4.33	42	external	1.9
5	4.23	11	internal	5.3
6	4.12	40	internal	6.3
7	3.79	38	external	7
8	2.56	202	internal	8.7
9	3.48	24	external	10

In the *sixth stage* the forecasting express assessment was carried out of the level of danger of the defects, which remaining life time is less than 10 years (Table 3). The calculation is performed for ten future moments of time  $t = 1, 2, \dots, 10$  years. The results are shown in Figs. 7 and 8.

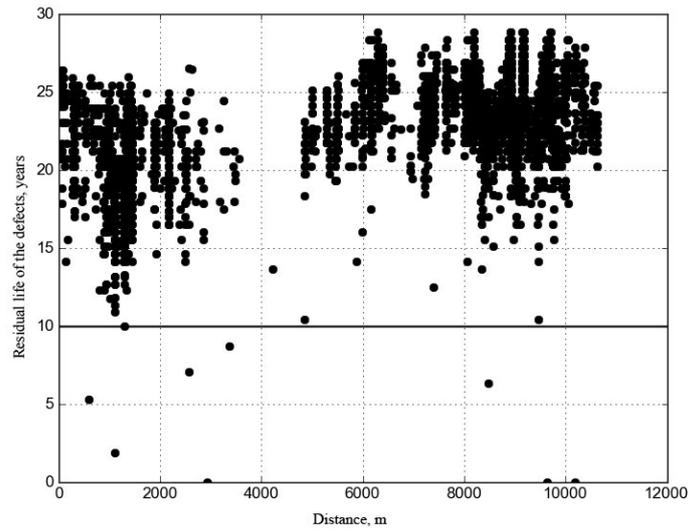


Figure 6. Residual life of the defective cross sections of the pipeline (assessments of true sizes of defects depths were used)

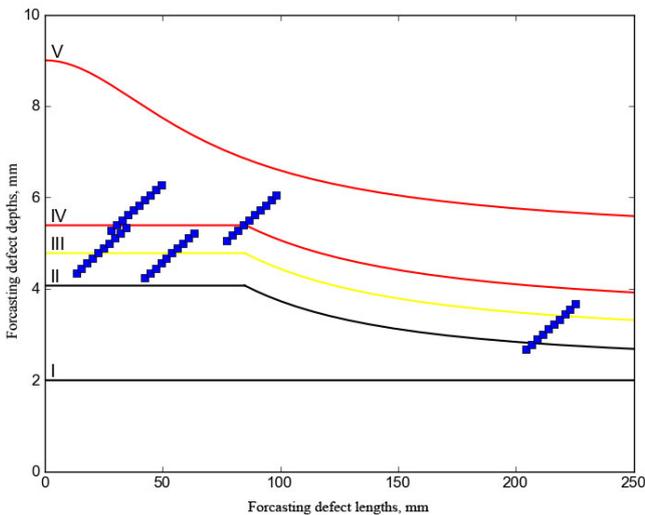


Figure 7. Forecasting express assessment of the level of danger of internal defects of the «loss of metal» type

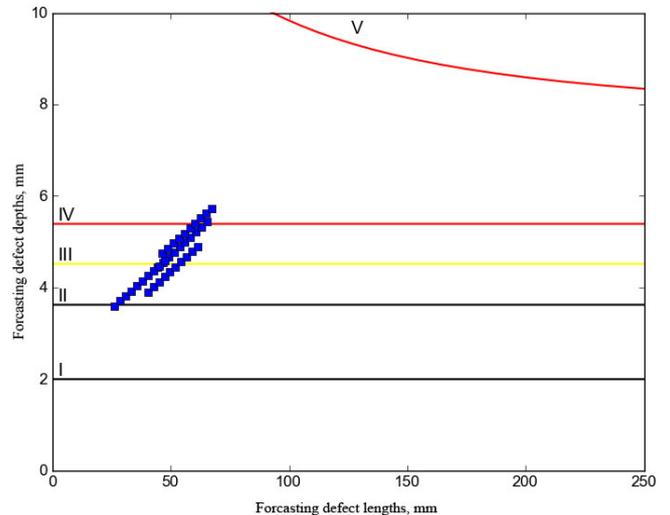


Figure 8. Forecasting express assessment of the level of danger of external defects of the «loss of metal» type

According to the obtained results one defect will require immediate repair after two years since the last ILI; one defect – after four years; one defect – after six years and one defect – after nine years. These defects will be dangerous in terms of loss of pipeline integrity by the “leak” type failure, because their depths, growing, outcross the horizontal red Line IV (60% *wt*).

Excluding from Table 3 all the defects which are subject to immediate repair, and repair within one year after the ILI, the residual life time and the gamma-percent residual life of the repaired pipeline obtain values as shown in Table 4.

Table 4

**Residual life of the pipeline**

Measurements used in the calculus of defects' depths	Pipeline residual life, years		Time to next ILI, years
	$\tau_{rl}$	$\tau_{rly}$	
<i>Assessments of true values</i>	8.70	8.67	7.67
Raw ILI tool measurements	10.00	9.88	8.88
Measurements of the ILI tool+ tolerance	7.1	7.05	6.05

According to the Table 4 it is recommended to execute the next ILI after 6 years (in 2011) since the last ILI.

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