USE OF TECHNICAL DIAGNOSTICS AT AN ASSESSMENT OF RISK OF FAILURE

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Abstract. The concept of risk is being more and more introduced in the process of industrial safety assessment. The insufficiency of risk analysis, using only traditional procedures, is shown in this document. Note that it is necessary to analyze the results of nondestructive testing and technical diagnostics (NDT-TD) in the process of risk assessment. TD includes a set of methods and procedures: Non-Destructive Testing (NDT), Fracture Mechanics (FM), metallurgy and corrosion analysis. So far, the methods of NDT and fracture mechanics are developed separately and without any interaction - except for the situation when it is necessary to determine a reject level. The logic of industrial safety requirements development has led to a necessity of NDT and FM joint efforts for an industrial safety assessment. Focus on data reception requirements, useful for the process of risk assessment, creates the necessity for the usage of criteria and characteristics that have not been considered properly yet in case of industrial NDT application. In particular, the characteristics binding real and measured defect size (calibration characteristics), POD, ROC and reliability matrix are the examples of such case. The current report provides a scheme of using NDT results for an assessment of fracture probability.

The development of ideas in the field of industrial safety has led to the need for a quantitative safety factor in the form of failure risk \( R \). It is described by a formula, which seems quite simple:

\[
R = P \cdot V, \quad (1)
\]

where \( P \) – failure probability (fracture, destruction), but as a rule, failure frequency index is used, \( V \) - assessment of consequences resulting from the failure. The formula (1), despite its apparent simplicity, involves the effects of many complex processes and it is very difficult to quantify each of them.

Scenarios of events, that follow the failure of a technical component, assessment of damage and possible deaths are included in the assessment of consequences \( V \). Current risk assessment techniques include (as primary operations) - hazard identification, development of failure scenarios, assessment of possible failure scenarios frequency, assessment of possible failure consequences under the given scenarios, calculation of failure risk indexes [1]. Most methods such as HAZOP, FMEA, Control List and others are mostly qualitative. As a result, we have a dispersion of estimates, reaching 2 - 4 orders of magnitude, and it is inadmissible for industry [2].

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Currently, the event rate (frequency), which is obtained at the statistical processing (failure number averaging), is usually used as the "input" of logical chain of event tree [3, 4]. This data is collected within several years, but it is not highly accurate. There is no data on technical condition of a particular technical component, which can be obtained only if the NDT and Technical Diagnostics (TD) are performed. In addition, as it is shown in the document [4], the rate of intensity (failure frequency) has a large dispersion, reaching the value of intensity magnitude. Figure 1a shows the dispersion of failure frequency estimates for pipe-related scenarios, figure 1b shows the statistics of failures for the main oil pipelines. [4]

![Figure 1a](image1.png)  ![Figure 1b](image2.png)

**Fig. 1a.** Failure frequency for pipe-related scenarios [3]  **Fig. 1b.** Statistics of failure risk for the main oil pipelines according to Rostechnadzor [4].
1- Average intensity of failures for the previous 5 years; 2 - Intensity of failures for 1 year; 3– 95% confidential interval for 5 years.

The vector of risk assessment development in the field of industrial safety is aimed at the usage of quantitative risk indicators with a decrease in their dispersion of estimates. But it is impossible without the transfer from statistical data on the number of failures at the unknown components over the past years to the data on an actual technical condition of a particular component. Such data can be obtained only when the technical diagnostics of a particular component is performed. Modern requirements for the quantitative assessment of risk cannot be achieved without the data on the real condition of technical devices, which can be obtained only after a set of works on non-destructive testing and technical diagnostics (NDT and TD). The main components of technical diagnostics are NDT, fracture mechanics (FM), corrosion analysis, metallurgy. To some extent, our term «Technical Diagnostics» coincides with the commonly used term «Inspection» (e.g., RBI). We define «Technical Diagnostics» as the assessment of technical condition of the equipment in order to evaluate industrial safety and residual life. At the same time, a measure of industrial safety is a failure risk index, and we should know the failure risk index at the end of the residual life period.

While estimating the technical condition of a component in order to assess failure risk it is necessary to know its stress-strain properties of the material and possible defects, which are both the objectives of TD. Modern requirements demand the knowledge of statistical distributions of both stress-strain properties of the material, including the heterogeneity of the material (phase composition and anisotropy of the structure) and defects statistics (their size, number, type, location). The critical parameters that influence the ultimate strength are the crack resistance of the material and its statistical distribution, as well as the sizes of the defects and their statistical distribution. Defect size growing and approaching the limit value at which the fracture occurs increases the risk of operation. According to the fracture mechanics models, the break-up of the component containing a crack occurs when stress intensity factor exceeds a critical value $K_c$. This criterion for bond-failure crack (mode I) looks as follows:

$$$$
where, \( a \) - crack depth, \( q \) - coefficient determined by the type of loading, size and shape of the structure, \( \sigma \) - applied stress index, and \( K_{lc} \) is determined by the stress-strain properties of the material. At a steady load and defect size increase, an uncertainty of the fracture moment (which determines the risk of fracture) is connected with an uncertainty of knowledge about the properties of the material \( (K_{lc}) \), and errors in crack size measurements \( a \) [5, 6].

Eventually the size of defect \( a \) (and accordingly \( d \)) increases (the area under crossing of distributions \( P_{\dot{a}1} \) and \( P_{f1} \), painted over by red), and the critical size of defect \( a_c \) decreases. It leads to increase in probability of fracture, that is schematically shown on fig. 2. Hazard rate of the defect, for example, the most dangerous defect - a crack, can be evaluated by comparing the depth of the crack \( a \) and the critical depth for a given component - \( a_c \). The critical size of the crack corresponds to the size at which the brittle (or quasi-brittle) fracture of the component \( \)occurs. This size is determined by the methods of fracture mechanics using the formula (2).

At the moment \( t_1 \) the depth of the crack is equal to \( a_1 \) (measured size \( \dot{a}_1 \)). It is necessary to take into account the uncertainty of knowledge of the crack size, which is given by the probability density function \( P_{\dot{a}1} \). The dispersion of a component material properties leads to scatter of the critical size of a crack, which is described by density of distribution \( P_{f1} \). At the same time, the risk of fracture \( P(t_1) \) is determined by the space under the intersecting curves of density probability \( P_{\dot{a}1} \) and \( P_{f1} \). Let’s suppose that \( P(t_1)=10^{-3} \). Eventually, the measured crack is increasing in size according to the law \( \dot{a}(t) \), the material properties undergo some degradation, and the critical size \( a_c(t) \) is decreasing, thereby the probability of fracture is increasing up to \( P(t_2)=10^{-3} \), for example, as shown in Figure.2. When the size of the crack reaches a critical size, i.e. the criterion \( a(t) = a_c(t) \) is met, the fracture of the component will occur.

Thus, the need for quantitative assessment (measurement) of fracture probability and the considered scheme initiate (burst and real) usage of a number of parameters and indicators for NDT, which had been previously invented, but have not been widely used in practice.
These indicators include a-hat-versus-a-graph (a→â-graph), graphs PoD and ROC, the indices of reliability and accuracy of the NDT methods.

First of all, let’s consider the usage of the measured defect size â to assess the risk of component fracture. The size of the defects obtained using NTD are used to calculate the strength of the component. To estimate the probability of component fracture it is necessary to use critical size of the defects a_c - probability of fracture relationship. The calculation results P(a_c) for different components of Nuclear Power Station are given, for example, in [7]. Figure.3a shows dependence of the fracture probability of the reactor pressure vessel on the defect size a_c, where the curve 1 - a conservative estimate, 2 - a realistic estimate, 3 - an optimistic estimate, 4 - acceptable level of fracture probability (10^{-7} per reactor a year) [7]. It should be noted that the curves similar to those shown in Figure.3, must be calculated for each component, the fracture probability of which is to be determined.

![Fig.3a. The dependence of the probability of component fracture (Pressured water type reactor) P(a_c) on the critical size of the defect a_c [7].](image)

![Fig.3b. The probability of reactor fracture P(a_c) and the probability P(â) of measured defect size non-exceedance μ = 5 mm.](image)

While assessing the probability of fracture using the measured defect size it is necessary to take measurement errors into account. The scheme of these errors recording is given in fig.3b. If the errors are distributed according to the normal law, the probability that the true size of the defect is less than the median (average) value is defined by:

$$P(\hat{a}) = 1 - \frac{1}{2} \left[ 1 - \operatorname{erf} \left( \frac{\hat{a} - \mu}{\sqrt{2\sigma^2}} \right) \right]$$

(3)

where \(\mu\) — average value of the measured defect size, \(\sigma^2\) — dispersion. Thus, by measuring the depth of the crack â, and using P(â) (curve 2 in fig.3b), it is possible to assess probability of component fracture, using the formula:

$$P_f = P(\hat{a}) \times P(a_c)$$

(4)

For the implementation of schemes Fig. 2 and 3 it is necessary to have data on component imperfection obtained using the following NDT characteristics:

1. Calibration characteristic – characteristic of defektometric correlation representing the dependence, which links the actual size of the defects and the instrument readings (a→â–graph).
2. The probability of defect detection PoD (Detectability) and, consequently, the probability of missing a defect (1-PoD).

3. Diagram of NDT informativity (ROC-diagram). In our practice, these diagrams are given in the form of "The reliability matrix".

The examples of these characteristics are given in Figures 4-6.

The main NDT indicator, which allows assessing the probability of component fracture at present, is a calibration characteristic (\(a \rightarrow \hat{a}\) – graph). It allows determining the parameters of defects using the data of NDT system (Figure 4).

For the implementation of the given approach it is necessary to have preliminary data about \(P(a_c)\), and also to know the value of \(\mu\) и \(\sigma\). For teams (companies) having high qualification of their NDT systems, these values must be known beforehand.

It should be noted that, as a rule, the measured size of defects have a significant dispersion (Figure 4), which must be taken into account when assessing the probability of fracture.

Another important characteristic that may affect the assessment of the component fracture risk, is the probability of detection PoD, which also serves as an indicator of NDT system quality (the system includes techniques, device, qualification of the operator). In case of detection of relatively large defect, the assessment of fracture probability is performed using the above mentioned method. The probability of two defects detection, each of which significantly affects the strength of the component is minor. As shown in [10], the fracture of the component usually occurs as a result of one maximum size crack. But by showing a plot PoD in coordinates OPoD-\(a/a_c\)O (\(a_c = a_0\) - the size of the defect, when the component destructs) or in coordinates OPoD-\(a/t\)O, where \(t\) - thickness of the component wall, we get an ability to assess the probability of catastrophic size undetected defect presence. Example of OPoD-\(a/a_c\)O - diagram is shown in Figure 5.

It is possible to assess the probability \(P_{\hat{a}m}\) of two "big" defects presence in the component, one of which is detected with a probability of PoD(\(\hat{a}_m\)) (the probability of
detecting already detected defect of the maximum size), and the other defect, which is larger in size, is not detected, but we can assume that it is present. While using the conservative estimate its size should be equal to the thickness of the component wall (i.e., the model "leak before break" is implemented) or to the value of the critical defect $a_c$. The probability of such a situation can be estimated by applying the multiplicative rule for independent events, and by subtracting the product from one:

$$P_{\Sigma} = P_{\text{fract}} = 1 - [1 - PoD(\hat{a}_m)] \times [1 - PoD(t)]$$  \hspace{1cm} (3)

$$P_{\Sigma} = P_{\text{fract}} = 1 - (1 - PoD(\hat{a}_m)) \times [1 - PoD(a_c)]$$  \hspace{1cm} (4)

To assess the probabilities, you can use formulae for PoD, for example, given in [11]:

$$P_i = \frac{\exp(\alpha + \beta \ln(a_i))}{1 + \exp(\alpha + \beta \ln(a_i))}$$  \hspace{1cm} (5)

Where $\alpha, \beta$—coefficients obtained as a result of an experiment.

The method expressed by formulas (3) and (4) makes it possible to estimate the probability of two "giant" defects presence, one of which is detected with a probability $PoD(\hat{a}_m)$, and the other is not detected with a probability of anti-PoD or $(1 - PoD(a_c))$. Anything may happen in practice!

Another important characteristic of the NDT system is the ROC-diagram (Receiver Operation Characteristic). This name originates from radiolocation (forties of the XX century). We call it the NDT Informativity Diagram (ID). The ID contains complete data characterizing the competence level of NDT system. In Russian practice this diagram is given in the form of "Reliability Matrix" [12, 13]. It combines PoD and PfD - the probability of false detection, i.e. - defect indication in case of defect absence.

An example of a traditional ROC-diagram is given in Figure 6.

Fig.6a. The Informativity Diagram of defects detection process by NDT system; arrows: 1-reduction of the signal/noise relation; 2-increase in competence of NDT system [14].

Fig.6b. Experimental data for Informativity Diagram NDT [15]; PfD – Probability of false Detection

It should be emphasized that PoD($a$) in Fig.6 is not a function of PfD, but the field of the diagram represents the complex quality characteristic of NDT system. Line 1 - the case when NDT system works under conditions in which the probability of defect detection and false defect detection – is equal. It means that it is a situation of full uncertainty (maximum entropy). In fig.6b there are points corresponding the operating results of various NDT techniques, obtained during experiments [11]. Recommended operating field of the NDT system: NDT: PoD($a$) $\geq$ 0,8 and PfD $\leq$ 0,2 (blue space in Figure 6a). As shown above, PoD characterizes the quality of NDT system and can be used in the process of assessing the fracture probability and PfD affects the cost of NDT results.

In practice, the data contained in the ROC-diagram is given in the form of "Reliability Matrix" [12, 13].
While using the above mentioned matrix, the certainty index is determined by the number of correct results \((n_{aa} + n_{rr})\) when performing \(n_{Σ}\) testings and is calculated as follows:

\[
R(\text{Reliability}) = \frac{n_{aa} + n_{rr}}{n_{Σ}}
\]  

Such diagrams as PoD(\(α\)) and ID-R in the practice of industrial NDT are not widely used now, however, to our mind, their use is inevitable, despite the fact that it would require significant investments, and improvement of NDT. We can state that the scientific base of NDT and TD, as well as methodological aspects have been worked through enough to use such indicators as the calibration characteristic, the rate of detection and informativity diagram in the process of fracture probability estimation. But for real development of these new approaches and their application it is necessary to establish relevant guidelines-standards.

**Conclusion.**

Thus, we can note a mutual positive impact of industrial safety assessment requirements with the usage of quantitative risk assessment and application of NDT→TD→QRA (Quantitative Risk Assessment). This requires the usage of industrial safety assessment methodologies, which had previously been invented, but have not been used in practice (these are: \(a\rightarrow\ddot{a}\) diagram, PoD, ROC, reliability index). And the use of methods NDT→TD allows improving the accuracy of risk assessment by several orders of magnitude. In fact, it allows giving the status of measurement process to the industrial safety assessment - measurement of industrial safety.

The use of NDT→TD in assessing the fracture probability allows:

1. Making the risk index a quantitative characteristic of industrial safety and reducing measurement error and calculation of risk.
2. To force further development of quantitative methods of risk and fracture probability evaluation (measurement) and the use of techniques in the field of NDT→TD, established in laboratories.
3. An opportunity to optimize industrial safety expenses and to put quantitative costs grounding into practice. In cases when the defect is detected and its size exceeds rejection standards, it is necessary to use an expert NDT and according to its results using metallographic analysis, determination of corrosion condition and evaluation using fracture mechanics methods to determine repair necessity or the possibility and terms of further exploitation. This will allow reducing downtime and cancelling useless repairs of technical devices.

**References**


