Chapter 2
Methods of Assessing Integrity of Pipeline Systems with Different Types of Defects

The following leading scientists have made significant contributions to the development of a theoretical base of integrity and probability of failure (reliability) assessment of pipeline systems: A.A. Aladinsky, M. Ahammed, J.A. Beaver, A. Bhatia, V.V. Bolotin, A. Bubenik, F. Caleyo, A.O. Chernyavsky, O.F. Chernyavsky, J. Collins, A.S. Copner, G. Desjardins, A.M. Edwards, A. Francis, A.G. Gumerov, P. Hopkins, O.M. Ivantsov, C.E. Jaske, J. Keifner, V.V. Kharionovsky, V.I. Kharitonov, H.O. Madsen, S. Mahadevan, G.P. Marsh, R.G. Mannapov, N.A. Makhutov, B.I. Miroshnichenko, V.V. Moskvichev, T. Morrison, G.Kh. Murzakhanov, M. Nassim, S.V. Nefedov, A.D. Palmer, M. Philips, J.N.K. Rao, D.H. Richardson, P.R. Stephens, V.N. Syzrantsev, W.A. Thompson Jr., S.A. Timashev, E.S. Vasin, P. Vieth, R. Worthingham, J. Zhou et al.

Consider the current state of the problems outlined in the Introduction.

2.1 Causes of Pipeline Failures

One of the main reasons for reduced strength capacity and destruction of pipelines is the appearance of local pipeline wall defects during its manufacture, construction, and operation [1–26].

Out of all defects of pipeline systems the corrosion defects proportion-wise are the most significant. Thus, over the period of 1999–2001 the percentage distribution of all failures in the Unified Gas Supply System looks as follows [20]:

- external corrosion—41.2 (including stress corrosion cracking—39.8);
- construction and assembly defects—17.6 (including weld defects—9.8);
- mechanical damage—8.8;

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- defects of pipes and connecting pieces—14.7;
- natural disasters—4.9;
- noncompliance with operational rules and standards—1.0;
- internal corrosion and erosion—2.9;
- other causes—9.8.

All types of local pipe wall defects occurring in pipelines have been defined and classified in [20, 22, 27–37] and numerous other works.

According to the VNIIGAZ data all pipeline defects fall into three classes [29, 30]:

- pipeline axis deviation from the design position;
- cross section shape irregularity;
- local pipe wall defects.

Defects of the linear part of a product pipeline are classified for maintenance purposes into five groups of parameters [29, 30]:

- by the nature of causes (metallurgical, welding, mechanical, corrosion);
- in association with a particular technological process (defects of steel sheets, pipe manufacturing, third-party damage);
- defects location (parent metal, plant weld, girth weld, weld thermal effect zone, lower pipe element, upper pipe element);
- location of defect inside the pipe wall or weld (surface, inner, through-defects);
- defects configuration (pitting, linear, large area).

VNIIST classifies main pipeline failures' causes into four groups [20]:

1. failures caused by pipe elements, check, and control valves;
2. construction defects;
3. violation of operation standards;
4. soil corrosion caused by research and design mistakes, use of low-quality materials, construction stage defects, violation of mode, and standards of operation.

According to [38], defects may be visible, hidden, as well as critical, significant and insignificant.

Analysis of literature on the subject allows stating that the most common types of defects identified during pipeline systems inspection are pipe wall surface defects, predominantly of the corrosion damage nature. There is no unified methodological approach to pipeline failure classification. In addition, analysis of consequences of operating pipeline failures and existing failure classifiers prove the relevance of using the stochastic approach when studying corrosion processes, as it adequately accounts for the multifactor nature of these phenomena when prognosing PS failure probability.

2.2 Pipelines Limit States

In the general case, the following limit states are considered for structural elements of the main pipelines linear part [12, 20, 21, 39, 40]:

- depletion of strength under a force impact (static and fatigue strength);
- loss of general (longitudinal) or local stability under compressive strain;
- depletion of pipe material plasticity;
- reaching the ultimate permissible lateral (in the vertical or horizontal plane) displacement by a structural element;
- pipeline rupture as a result of wall thinning, caused by corrosion and (or) inner surface erosion;
- integrity loss as a result of local deformations (local corrosion, defect opening, random mechanical impacts);
- extended fracture caused by crack(s) propagation;
- underwater and aboveground pipelines movement under the dynamic impact of water or air pressure;
- avalanche-type buckling of a deep-water pipeline under the water column pressure, etc.

Analysis of pipelines operation over many years [30, 41–44] demonstrates that their linear segments predominantly fail in two modes: leak and burst [45, 46]. Both limit states are considered in this book.

A *leak* is a disruption of a pipeline integrity due to appearance of micro-holes which manifest themselves by a limited leakage rate (up to several liters per minute).

Burst, destruction, or guillotine-type rupture is the pipeline destruction across its cross section up to a complete rupture. This type of failure is the most dangerous and often causes severe ecological and economic consequences.

Actual pipeline reliability assessment requires taking into consideration all the aforementioned types of limit states. This book presents pipeline reliability assessment problems under the simultaneous effect of two factors—various types of active corrosion and operating pressure.

2.3 Analysis of In-Line Inspections (ILI) Results

The degradation processes occurring in a PS (corrosion, erosion, cracks propagation, etc.) lead to the appearance of various physical and geometrical defects, which affect the general characteristics of system operability. In this connection, it becomes necessary to know the sizes of these defects, and how they change in time. This is done by regular ILI during which the defect parameters are registered (depth, length, width, angle position relative to the pipeline axis, etc.).

The main task of technical PS diagnostics is timely assessment of pipeline technical condition due to change of operational regimen, interaction with the environment, and accumulation of all kinds of defects. Inspection results serve as the basis for assessing pipeline residual life, and selecting the most efficient type of maintenance.

Information obtained during an inspection consists of data on the pipeline material metallurgical anomalies, other types of defects, their location, orientation along the longitudinal axis and across the pipe circumference (perimeter), as well as their dimensions (length, depth, width). This information inevitably contains some constant and random inherent built-in measurement errors (ME), since it is physically impossible to create measurement tools free of any measurement errors. These ME may significantly distort the real state of the studied system.

Studying a PS integrity and its *fitness-for-purpose*, it is necessary to take into account these ME while using ILI results. Conclusions made on the basis of these "contaminated" data about the state of a technological system and the required integrity and reliability protection actions may prove to be inadequate and (or) late. This, in its turn, may result in incidents, accidents, and disasters with huge material damage and loss of life/limb.

Because of ME, the diagnostics methods per se are not capable of producing true values of the measured parameters. The results of defects parameters measurements are just an approximate evaluation of the true values. The following factors affect the control reliability:

- physical limitations of the measurement tool;
- quality and integrity of the instrument being used;
- state of the objects surface in the control zone;
- conditions of control;
- time of control;
- visual acuity and physical condition of the inspector/diagnostician;
- qualification and the psycho-physiological condition of the inspector.

Currently, a sufficiently developed general theory of measurements and their statistical analysis are as follows [43, 47–61]:

- the general theory of measurements and their statistical analysis;
- the theory of measurement tools and calibration testing;
- scientifically justified set of ILI quality metrics, as applied to thin-walled cylindrical pipelines (see Chap. 4).

The level of application of this theory in practice of sizing defects in various purpose pipelines is quite insufficient.

The consequences of such situation are accidents on critical pipeline systems. For instance, it is well known that the accident on the USA nuclear facility "*Three Mile Island*" was caused by a defective steam pipeline burst, which was diagnosed shortly before the accident as faultless. Consequent verification of qualification level of the certified personnel which carried out the inspection of the failed steam pipelines by the United States Nuclear Regulatory Commission *NUREG* in accordance with the so-called round robin test (inter-laboratory verification of MI and measurement results performed by different inspectors) demonstrated an unacceptable accuracy spread between measurements of the same defects performed by one and the same tool from one specialist to another, and from one group of inspectors to another, notwithstanding their legally identical qualification certification levels [62].

ILI inspection is not yet capable of providing ultimate solution to all the problems of safe PS operation. Statistics of real incidents on pipelines demonstrate that many accidents occur early on, or right after the "successful" inspection completion. This may be explained by the fact that even the state-of-the-art in-line (external) measurement tools often incorrectly detect (identify) or underestimate (overestimate) the sizes of the defect parameters. Analysis of accidents on the USA oil pipelines, which occurred soon after a successful inspection (within 3–12 months), performed by the US Department of Transportation in 2005, demonstrated that causes of these disasters were [63, 64]: omission of serious defects (51 %), underestimation of the defects sizes (32.4 %), and wrong identification (16.6 %). As a result, the potential danger of discovered defects severity is not always adequately recognized.

Hence, it is obvious that, when assessing severity of a defect, the consistency of this assessment depends on the accuracy of determining the values of its parameters. In this connection, the following should be provided by inspection vendors about the results of a specific PS: (1) probability of detecting defects; (2) probability of correct identification of the detected defects; and (3) accuracy of measurement of the defects parameters, or the ME of the used measurement tools.

Most common measurement instruments (MI) used in ILI of oil pipelines are magnetic tools. In modern high-resolution HRMFL tools the ME tolerance (with regard to measuring the depth of the "metal loss" type defects) normally corresponds to about 10 % wt of the pipe wall thickness at 80 % confidence interval (CI). For MFL tools with super high resolution, the ME equals 5 % wt at 80 % CI. In case of ultrasound type (UT) tools with high and super high resolution, the defect depth measurements demonstrate tolerance of 1.0 and 0.5 mm, respectively, at 95 % CI.

ILI accuracy is established by means of verification, i.e., by additional control (another, independent measurement). Currently, in practice only a small part of detected defects is subjected to verification. This procedure may involve the use of different tools: laser, UT, visual control, wall thickness, as well as welder universal template, etc. While comparing results of the original inspection and verification, it can be seen that, practically in all cases, the results of inspection, in addition to random ME, contain also constant (average and multiplicative) errors, which, to make calculations simpler, usually are neglected [65].

Existing approaches to inspection quality assessment are mostly based on mathematical models, which describe measurements as containing only random errors and neglecting systemic errors (the average and the multiplicative MI bias). Figure 2.1[1] shows the ratio of the depth of the verified corrosion defects to the depth of the same defects measured by the ILI tool. From Fig. 2.1 it is obvious that the true size of defects depth was severely underestimated: by half, on average ($\lambda_{cp} = 2$). From this it follows that for correct sizing of corrosion defects, it is necessary to take

[1] Figure 2.1 is taken from the Proceedings of the OOO VNIIGAS Conference "Innovative potential of young scientists and specialists of OOO VNIIGAS," 2015, vol. 1, p. 242.

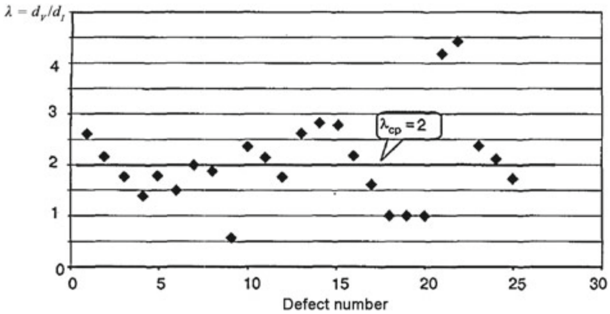

Fig. 2.1 Ratio of corrosion defects depth d_V, measured by local methods (verification) to the defects depth d_I, measured by ILI tool (russian gas pipeline "Urengoi–Surgut–Chelyabinsk–2")

into account both systematic and random errors. This is possible only when using mathematical measurement models which account for both types of MEs.

For compensation of the MEs, which inevitably occur during any inspection, most of the standards and industry guidelines use certain permanent values (called tolerance). For instance, the "*Gasprom*" Standard [41] recommends, for ME compensation, adding 1 mm to the depth of each defect. In the industry standard [66] the defect parameters (depth, length, width) are multiplied by a correction coefficient, depending on defect type and the mathematical model of the used measurement tool. Apparently, these tolerances were assigned according to the results of statistical analysis of measurement obtained in laboratory conditions, or on the basis of statistical accuracy of the instrument. In reality, this tolerance (MI accuracy) changes each time when one and the same MI is used in different pipes, and when it is repaired or modified. If we were to add, according to [41], $c = 1$ mm to each measurement obtained during ILI inspection, then in case of overstating by the ILI tool of the defects depth, it would make them even deeper. This would have a negative effect, when assessing the pipeline state and result in premature and costly repairs.

In fact, the rate of depth growth a_d (assuming its linear) would not change, if corrected by adding tolerance to its value:

$$\frac{(d_L + c) - (d_P + c)}{t_L - t_P} = \frac{d_L - d_P}{t_L - t_P} = a_d,$$

where d_L, d_P are, correspondingly, the defect depth according to the latest and the second last inspection, respectively; $t_L - t_P$ is the time interval between inspections.

Indeed, already when using the simple criterion of the critical, "leak," state of defect (defect depth equals 80 % of the pipe wall thickness wt), obtain

$$d(t) = d_L + c + a_d t,$$
$$t_{res} = \frac{0.8wt - d_L - c}{a_d} = \frac{wt - d_L}{a_d} - \frac{c}{a_d}.$$

Thus, the defect residual life according to the "leak" criterion t_{res} is reduced by c/a_d. According to the same "*Gazprom*" Standard [41], based on generalizing results of diagnostics of a set of pipelines transporting corrosive substances, it was found that after 15 years of their operation, the corrosion rate on the pipe inner surface reaches 0.253 mm/year, and on the outer surface CR is 0.206 mm/year, at a confidence probability of 90 %. In other words, if 1 mm is added to the depth of each defect, the external defects residual life according to the "leak" criterion will be reduced by almost 5 years, and the residual life of internal defects will be 4 years shorter. When conducting calculations, the verification instrument (VI) is often considered as absolutely accurate and, on this basis, an assessment of the second measuring tool accuracy (presumed less accurate) is made. Assuming ideal VI (MEs are equal to zero) may result in that any MEs of VI can be attributed to the used ILI tool, which will lead to unjustified worsening of its quality assessment. This has to be taken into account when evaluating quality of the diagnostician or of an early diagnosis.

Thus, it should be acknowledged that existing methods of analyzing ILI results for obtaining estimates of the true values of detected defects sizes are insufficiently substantiated. Therefore, the degree of potential danger of defects is not always determined correctly, and may lead to contradictory results. This does not allow obtaining consistent estimates of integrity and probability of failure (reliability) of inspected objects.

In the past, the quality of used ILI tool was not subjected to detailed analysis. At present, important work is carried out to inter-calibrate the inspection tools being used, so as to obtain generalized characteristics of their operation in real-life conditions [64, 67–70]. The problem of optimal means and methods for detecting defects in pipelines is discussed in [65]. In a number of articles [49, 51, 52, 71] the current level of ILI accuracy is comprehensively reviewed. In [72, 73] one of the authors of this book suggested and substantiated a set of seven basic metrics of ILI tools quality (for details see Sect. 4.3). On their basis, it is possible to make more accurate estimates of POF, residual strength, and remaining life of pipelines, as well as assign optimal time of their next diagnostics.

Another problem consists in that the results of any ILI do not give the true number of actual defects. The set of defects detected by the used ILI tool contains, as a rule, a subset of false defects. This can have a serious negative impact on the accuracy of pipeline reliability assessment. Moreover, according to the full stochastic classification of pipe defects, based on the results of inspections (proposed, as far as we know, in 2002 [5]), the set of each type of defects, found in the ILI data, can be divided into four groups, namely true (correctly detected) defects, false (phantom) detects, falsely undetected (missed) defects, and correctly undetected defects (areas without defects). The first three of these four subsets are of the greatest interest because they directly affect the reliability of pipelines. However, even in the API Standard 1163 [74] the probability of nondetection of defects was excluded from direct examination. Currently, among pipeline diagnosticians there exists a growing recognition that all three groups of defects—the true (correct detection), falsely detected, and falsely undetected defects—should be taken into account when evaluating pipeline POF [5]. Moreover, these three subsets of each type of defects, if known, allow estimating the actual number of each type of defects in the pipeline, through a certain correction procedure. One of the most effective methods for correcting probabilistic assessment of pipeline physical parameters is developed based on the Bayesian approach. It finds wide application in various fields of science and technology [1–4, 6, 75].

In this book, the authors propose methods of updating the true number of defects in a pipeline after ILI and subsequent verification of the ILI results by a second, independent, measurement tool.

2.4 Analysis of Existing Corrosion Degradation Models of Pipeline Systems

Corrosion is a spontaneous destruction process of metals as a result of environmental (including atmospheric) exposure, accompanied by energy release and diffusion of matter (entropy increase). The rate of corrosion is expressed via change of the material mass, depth of corroded pipe surface, formation of pittings, amount of corrosion products, change of pipe material tensile strength, yield strength, or its deformation.

By the early 1980s, a sufficiently full classification of corrosion models was developed [20]. As a result of studies [58, 60, 76–93], the following quantitative models were developed:

- empirical dependencies for assessing metal corrosion losses, taking into account up to four random parameters;
- random multiparameter corrosion regression models;
- mathematical multiparameter models with a large number of correction coefficients based on statistical representation of corrosion kinetics, without accounting for the duration of the corrosion process;
- models describing corrosion of metals (in different aggressive environments), using nomograms and table coefficients;
- cybernetic models with inner feedback in a corrosion pair, which permits prognosis of the corrosion process flow;
- specifically tailored mathematical models (for describing atmospheric corrosion, of aluminum, underground corrosion of steel in various types of soil, sea corrosion, etc.);
- mathematical models built on the basis of data about actual corrosion metal losses.

A large number of corrosion studies were conducted in the 1980s, based on laws of electrodynamics [20], and methods of electrochemical corrosion calculation were being developed [94].

Currently, a large number of mathematical models are available for describing the kinetics of steel corrosion process based on experimental data. These models could be grouped into five categories [20, 22, 76–78, 84, 87, 92, 93, 95–101]:

- models taking explicitly into account time, aggressive environment properties, metal properties, etc.;
- specifically tailored environmental corrosion models (atmospheric corrosion of different grades of steel, aluminum and aluminum alloys, sea corrosion of various materials, etc.);
- probabilistic models, developed using information from a limited number of tests, which may be extended on the whole general sample set, including analogs, which well correspond to the experimental data by certain criteria;
- models based on the study of actual corrosion metal losses for a specific case. Adequacy of these models to real-life processes depends on the available volume of experimental results;
- models, describing the corrosion process by certain types of functions [73, 76, 84, 92, 102–105].

Vast majority of these studies consider each defect separately. Using this approach for assessing pipeline segment reliability may produce misleading results. To correctly address this problem, it is necessary to consider simultaneously behavior of the whole set of defects on a given pipeline segment.

This book offers an overview of probabilistic methods used for describing corrosion of the whole set of defects detected on a given pipeline segment described as a Markov pure birth process. Using this approach in combination with random value models of other pipeline parameters allows calculating the conditional POF of a PS according to the leak criterion under the joint effect of operating pressure and active growth of pipe wall corrosion defects.

2.5 Analysis of Residual Strength of Main Pipelines Segments with Localized Corrosion Defects

One of the main reasons for PS destruction is decrease of their strength capacity due to the development of local defects in pipe wall. Most of these types of accidents occur due to surface-type defects. The term *surface-type defect of either external or internal pipe surfaces refers to* the following types of damages:

- corrosion caverns (general, spot, pit, rill corrosion, etc.);
- erosion wall thinning (due to the abrasive impact of small solid particles on the inner pipe wall surface, present in the transport flow);
- mechanical damage (dents, scuffing, nicks, etc.) inflicted during pipeline excavation;
- cracks (SCC, high-, and low-cycle fatigue cracks).

In addition to surface defects, technological defects (lamination, cracks, rolling laps, different metallurgical anomalies of pipe material, etc.) also may be dangerous, as well as various weld defects. Defects can also be classified as (1) longitudinal and (2) circumferential. In longitudinal defects their size along the pipeline axis is greater than their size across the pipe perimeter; it is vice versa for the circumferential defects. Residual strength assessment of the defective pipe segment depends both on the defect type and on its orientation relative to the pipeline axis. Classical deterministic methods of strength analysis [8, 21, 39, 106–111] are not suitable for obtaining a full solution of this problem. Assessment of pipeline structural reliability under this approach is performed on the basis of solving a deterministic strength problem, applied as a rule, to the most vulnerable defective pipe section [20]. In this case, the following strength analysis sequence is being used:

- detect most loaded pipeline system segments;
- determine forces and moments acting on the segments boundaries;
- study the stress–strain state (SSS) of linear pipeline segments using the girder- or strut-type finite elements, taking into account the already known force factors;
- conduct more comprehensive SSS analysis of the most critical segments, using shell-type and 3D-type finite elements;
- analyze the bearing capacity of the vulnerable pipeline segments using strength and destruction criteria.

On the one hand, in strength analysis advanced solid body mechanics methods and criteria are used, which adequately reflect fracture processes. On the other hand, to compensate for the random character of the loading, manufacturing, and operation errors, different safety factors are introduced, which, as a rule, are set in accordance with the pipelines design and operation experience. This resulted in certain discordance in the existing codes and methodologies when accounting for various factors, which affect structure weight and strength [20]. To eliminate this discordance it is necessary to account for the random nature of a multitude of factors, which contribute to pipeline structure operation and determine the random character of its loading and the level of stress and strain state under different operation modes.

Currently, the most internationally recognized methodology for assessing the residual strength of longitudinally oriented surface (external or internal) corrosion defects is the code developed by the American Society of Mechanical Engineers (ASME). The initial code, ASME B31G, was adopted as the US national standard [112] and, in simplified form, as the national standard of Canada [113]. Subsequently, the modification of this standard was developed, which is called B31Gmod [114]. In addition to the codes B31G and B31Gmod widely used methodologies are DNV [115], Battelle [116], and Shell-92 [117]. These methodologies are also used (with some modifications) for designing water mains, subsea pipelines, hydraulic systems of nuclear power plants NPP, ships, and aircrafts, as well as pulp transportation pipelines. Design of some specific PS is also based on codes [114, 115].

All the above practical methodologies [112, 114–117] are based both on theory and extensive experiment, conducted on real scale pipes. Their essence [118] is in that the design estimate of the burst (failure) pressure for pipeline defective cross section is derived using formulas obtained from linear relationships of the theory of strength of materials, by introducing into them some empirical factors, which account for the physical nonlinearity of pipe material. Such factors, obtained from analysis of a large number of pipe segments, subjected to field tests, include the following:

- Folias factor—a coefficient, which connects defect parameters with pipe geometry;
- Flow stress, which is the stress required to create plastic strain in the pipe metal (effective yield strength). It accounts for the effect of metal strengthening under load.

For calculating the residual strength of a pipeline segment with longitudinally oriented defect, the B31G, B31Gmod, Shell92, and DNV codes use the semi-empirical criterion of plastic fracture equation in the form [119]

$$\sigma_h = \sigma_f \frac{A_0 - A}{A_0 - AM^{-1}} = \sigma_f \frac{1 - \frac{d}{wt}}{1 - \frac{d}{wt.M}}, \tag{2.1}$$

where σ_h are the hoop fracture stresses of pipeline segment with a single defect; σ_f are the yield stresses; $A_o = l \cdot wt$ is the initial area of the longitudinal cross section of the damaged pipe segment, where l is the maximum length of the defect along the pipe axis, wt is the pipe wall thickness, $A = ld$ is the area of defect in the longitudinal cross section of the defective pipe segment, where d is the maximal defect depth; M is the Folias factor.

Criterion (2.1) describes the fracture stresses of a pipe under internal pressure caused by a longitudinally oriented defect. This criterion is based on the fracture of thin-walled cylindrical shells with a surface crack.

In high-pressure vessels (vessels, pipelines, etc.) an axial crack may develop. Hoop stresses acting across this crack and created by the pressure inside the pipeline are calculated by the Gadolin–Barlow formula [120, 121]:

$$\sigma_h = \frac{PD}{2wt}, \tag{2.2}$$

where P is the pipeline pressure and D is the pipeline outer diameter. For aboveground pipelines $P = P_{int}$, for underground pipelines—$P = P_{int} - P_{ext}$, where P_{int} is the inner pressure in a pipeline; P_{ext} is the external pipeline pressure; $P_{int} > P_{ext}$.

Crack propagation or destruction will occur when its opening (growth of the distance between crack faces) reaches a critical value (CCO). CCO is the critical crack opening at its tip, which is a plastic deformation parameter at the crack tip. According to Dugdale [122] (this is the most suitable scheme for pressure vessels and pipelines), the CCO is calculated by the formula [123]

$$CCO = \frac{8\sigma_f^2 l}{\pi E} \ln\left[\sec\left(\frac{\pi\sigma}{2\sigma_f}\right)\right], \tag{2.3}$$

where E is the elastic modulus, which characterizes the material resistance to tensile (compression) stress under elastic strain; l is the crack half length; and σ_f is the rupture stress.

Stress intensity factor K_I (SIF) is related to CCO by the formula

$$CCO = \frac{K_I^2}{E\sigma_f}. \tag{2.4}$$

SIF is the stress singularity measure around the crack tip used for describing stress fields near the crack tip.

Substituting σ with $M_h\sigma_h$, from Eqs. (2.3) and (2.4) obtain that SIF is calculated by the following formula [123]:

$$K_I^2 = \frac{8\sigma_f^2 l}{\pi} \ln\left[\sec\left(\frac{\pi M_h \sigma_h}{2\sigma_f}\right)\right], \tag{2.5}$$

where M_h is the stress intensity growth factor.

Factor M_h accounts for the experimentally observed fact of crack faces buckling outward under pressure.

It may be expected that fracture will take place at $K_I = K_{Ic}$, where K_{Ic} is the fracture toughness of the material, which describes the material ability to resist the beginning of crack movement and propagation under mechanical and other types of impact.

Using the formula (2.5), it may be shown that at high values of $\frac{K_I^2\pi}{8\sigma_f^2 l}$ the value of expression $\frac{M_h\sigma_h}{\sigma_f}$ approaches unity [123]. In these cases, destruction is independent of fracture toughness, and the fracture criterion takes the form [123]

$$\sigma_h = \sigma_f M_h = \sigma_f \frac{1 - \frac{d}{wt}}{1 - \frac{d}{wt \cdot M}}. \tag{2.6}$$

where M is the Folias factor.

According to this criterion, fracture occurs when the general yield occurs, or a bit later [123]. The general yield means that the body acquires the property of unlimited plastic deformation, i.e., deformations increase significantly without any increase of external loading.

Relatively recently (2000) on the basis of studies conducted in the Battelle Institute, of the fracture mechanism for actual pipes, the PCORRC (Battelle) methodology was developed [116]. Under this methodology, for high resilience pipe steels, unlike in expression (2.1), the equation for determining the hoop stresses, arising as a result of a defective pipeline segment destruction, has the form

$$\sigma_h = \sigma_f \left(1 - \frac{d}{wt} M\right). \tag{2.7}$$

When assessing the influence of other loads on the hoop and axial stresses, e.g., high temperatures, soil movement, or seismic activity, their detailed modeling is required. In these cases it is advisable to use the finite element method [124–127].

Substituting into the formula (2.6) the expression for hoop stress (2.2), it is possible to determine the failure pressure of a defective pipeline segment at time t:

$$P_f(t) = \frac{2wt \cdot \sigma_f}{D} \frac{\left(1 - \frac{d(t)}{wt}\right)}{\left(1 - \frac{d(t)}{wt \cdot M(t)}\right)}. \tag{2.8}$$

The expression (2.8) for evaluating failure pressures in each of the codes (B31G, B31Gmod, Shell92, or DNV) is different, depending on the expressions used for the Folias factor M, flow stress σ_f, and on how geometric shape of the defect is approximated. For the PCORRC code the expression for failure pressures is obtained from (2.7) taking into account (2.2).

Expressions for calculating the Folias factors were obtained by analyzing hydrostatic testing results of a large number of main pipelines with corrosion defects [118].

According to [120], all methods are classified as the SMYS-based and the UTS-based, where SMYS and UTS are specified minimum yield strength and ultimate tensile strength of the pipe material, respectively. UTS-based methods use the ultimate tensile strength of pipe material to define destruction of the pipeline defective cross section.

The described above codes can be applied only to a single cross section of the pipeline containing a longitudinally oriented, flat bottom surface defect of the corrosion/erosion type. The methodologies are based on the assumption that the defective pipe segment failure occurs as a result of plastic fracture [120].

We consider each methodology in detail.

B31G code [112]. In this methodology a surface defect in the longitudinal (axial) section of a defective pipe segment is approximated by a parabolic form (see Fig. 2.2) and the effective defect area (highlighted in gray) in this section is calculated as $\frac{2}{3}d \cdot l$.

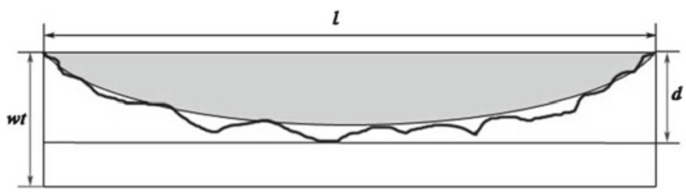

Fig. 2.2 Parabolic approximation of the surface defect in the pipeline longitudinal cross section, according to B31G code

The Folias factor is calculated by the formula

$$M_1(t) = \sqrt{1 + 0.893\frac{l^2(t)}{D \cdot wt}}. \tag{2.9}$$

The flow stress $\sigma_f = 1.1SMYS$.

The formula for failure pressure of a pipeline segment with a surface longitudinally oriented corrosion/erosion type defect has the form

$$P_f(t) = \frac{2wt \cdot 1.1SMYS}{D} \cdot \frac{\left(1 - \frac{2}{3}\frac{d(t)}{wt}\right)}{\left(1 - \frac{2}{3}\frac{d(t)}{wt \cdot M_1(t)}\right)}. \tag{2.10}$$

Maximal admissible length of defect with depth $d(t)$ is calculated by the formula

$$l_{\max}(t) = 1.12B(t)\sqrt{D \cdot wt},$$

where parameter $B(t)$ equals

$$B(t) = \sqrt{\left(\frac{d(t)/wt}{1.1d(t)/wt - 0.15}\right)^2 - 1}.$$

Formula (2.10) applies to defects which length $l \leq 4.48\sqrt{D \cdot wt}$. For longer defects ($l > 4.48\sqrt{D \cdot wt}$) the fracture pressure is determined by the formula

$$P_f(t) = \frac{2wt \cdot 1.1SMYS}{D} \cdot \left(1 - \frac{d(t)}{wt}\right). \tag{2.11}$$

The code is applicable only to pipes, which material class is below the X56 API 5L standard [128] (i.e., SMYS and UTS are less than, respectively, 386 and 489 MPa). The defects depth must be within the (10–80 %) range of pipe wall thickness.

This code should be applied only to

- a single cross section of the pipeline containing a longitudinally oriented, flat bottom surface defect of the corrosion/erosion type;
- pipes, which material class is below the X56 API 5L standard [128] (i.e., SMYS and UTS are less than, respectively, 386 and 489 MPa);
- defects which depth is within the 10–80 % range of pipe wall thickness.

B31Gmod code [114]. Modification of B31G code consists in the change of expressions for flow stress, Folias factor, and the estimated parabolic form of defect (factor 2/3 in formula 2.10) is replaced with an arbitrary one. For this purpose a correction factor of 0.85 is introduced.

The Folias factor is calculated by the formula

$$M_2 = \begin{cases} \sqrt{1 + \frac{62.75 \cdot 10^{-2} l^2(t)}{D \cdot wt} - \frac{33.75 \cdot 10^{-4} l^4(t)}{(D \cdot wt)^2}}, & \frac{l^2(t)}{D \cdot wt} \le 50, \\ \frac{3.20 \cdot 10^{-2} l^2(t)}{D \cdot wt} + 3.3, & \frac{l^2(t)}{D \cdot wt} > 50. \end{cases} \tag{2.12}$$

The flow stress $\sigma_s = SMYS + 68.95\,\text{MPa}(10\,\text{ksi})$.

Failure pressure for a pipeline segment with a longitudinally oriented defect of the corrosion/erosion type is calculated by the formula

$$P_f(t) = \frac{2wt\,(SMYS + 68.95\text{MPa})}{D} \frac{\left(1 - \frac{0.85d(t)}{wt}\right)}{\left(1 - \frac{0.85d(t)}{wt \cdot M_2(t)}\right)}. \tag{2.13}$$

This criterion uses a more accurate expression for the Folias factor than the code B31G, and is less conservative [120].

The restrictions of this code as compared to applicability of the B31G code have one difference: the defects depth can reach 85 % of pipe wall thickness.

DNV code [115]. Unlike the B31G and B31Gmod codes, the DNV methodology takes into account other loading conditions, including the compressive axial loads. This code is a result of a joint industrial project of *"Det Norske Veritas*" (Norway) and "*BG Technology*" (Canada). These companies have created a vast database of real-life pipe samples subjected to rupture tests, with a single corrosion defect and several interacting corrosion defects of irregular shape. Alongside with these experimental data, a large number of three-dimensional nonlinear finite element pipe models were built, which were subsequently verified with experimental data, the results of which have been used for developing this criterion [120].

In this approach the defect is approximated by a rectangular form (Fig. 2.3) and the area of surface damage in the axial pipeline cross section is calculated as $d \cdot l$.

The Folias factor is calculated by the formula

$$M_3(t) = \sqrt{1 + 0.31 \frac{l^2(t)}{D \cdot wt}}. \tag{2.14}$$

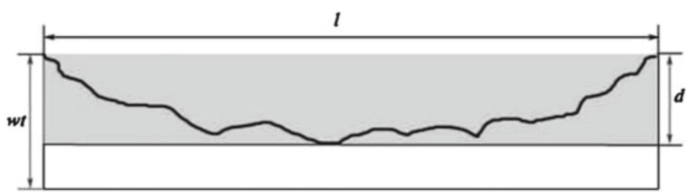

Fig. 2.3 Rectangular shape approximation of a surface defect in the longitudinal cross section of the pipeline, according to DNV methodology

The flow stress is equal to UTS.

A formula for failure pressure of a pipeline segment with longitudinally oriented surface defect of the corrosion/erosion type has the form

$$P_f(t) = \frac{2wt \cdot UTS}{D - wt} \frac{\left(1 - \frac{d(t)}{wt}\right)}{\left(1 - \frac{d(t)}{wt \cdot M_3(t)}\right)}. \quad (2.15)$$

This code should be applied only to

- single cross section of the pipeline containing a longitudinally oriented, flat bottom surface defect of the corrosion/erosion type;
- defects which depth is less than 85 % of pipe wall thickness.

Shell92 code [117]. As in the case of DNV code, the defect is approximated by a rectangular form (see Fig. 2.3).

The Folias factor is calculated by the formula

$$M_4(t) = \sqrt{1 + 0.805 \frac{l^2(t)}{D \cdot wt}}. \quad (2.16)$$

The flow stress in this code is equal to $0.9UTS$.

A formula for failure pressure calculation of a pipeline segment with a surface longitudinally oriented defect of the corrosion/erosion type has the form

$$P_f(t) = \frac{2wt \cdot 0.9UTS}{D} \frac{\left(1 - \frac{d(t)}{wt}\right)}{\left(1 - \frac{d(t)}{wt \cdot M_4(t)}\right)}. \quad (2.17)$$

This code should be applied only to

- single cross section of the pipeline containing a longitudinally oriented, flat bottom surface defect of the corrosion/erosion type;
- defects which depth is less than 85 % of pipe wall thickness.

PCORRC (Battelle) code [116]. PCORRC methodology was developed on the basis of studying the mechanism of destruction of pipes, material of which has improved or high fracture toughness, and on the high-precision modeling of the finite element pipe models performed at the "*Battelle*" Institute [129]. According to field test results of a large number of actual pipe segments, the destruction mechanism for defective pipeline segment depends on the pipe material fracture toughness. These tests also showed [120] that only pipes made out of steel with improved or high fracture toughness fail a result of plastic fracture. In determining the Folias factor the effect of increased stress concentration and steel hardening in the plastic deformation zone at the start of the defect failure process was taken into account.

According to PCORRC, the failure pressure for a pipeline segment with a longitudinally oriented defect of the corrosion/erosion type is calculated by the formula

$$P_f(t) = \frac{2wt \cdot UTS}{D} \cdot \left(1 - \frac{d(t)}{wt} M_5(t)\right), \tag{2.18}$$

where the Folias factor is calculated by the formula

$$M_5(t) = 1 - \exp\left[-0.16 \frac{l(t)}{\sqrt{\frac{D}{2}(wt - d(t))}}\right]. \tag{2.19}$$

This code should be applied only to

- a single cross section of the pipeline containing a longitudinally oriented, flat bottom surface defect of the corrosion/erosion type;
- pipelines, which operate at temperatures exceeding the temperature of pipe material ductile–brittle transition, and for pipe material with the impact energy of Charpy 61 J and above [116].

2.6 Assessment of Pipeline Systems Reliability

A lot of attention is being paid worldwide to the problem of improving pipeline systems structural and operational reliabilities [17, 20, 21, 28, 43, 106, 130–148].

All methods of reliability assessment of thin-walled cylindrical shell systems (pipelines) may be classified as methods based on the RVs theory and the theory of various types of random functions (RF) or fields. Methods based on RV theory are more common. These, in their turn, may be broken down into methods, which reduce the plethora of probability density functions PDFs, used to describe the random parameters, to the Gaussian normal law, and to methods which operate directly with non-Gaussian PDFs. The former methods go back historically to the works of Freudanthal, N.S. Streletskyand, and A.R. Rzhanitsyn.

A universal, but practically unrealizable, straight forward method for solving high dimensionality reliability problems is the method of direct n-fold integration of a n-dimensional joint PDF of parameters, which describe the condition of a structure, over an admissible domain in the space of the design parameters. Even for a relatively small value of n and irregular complex shape of the admissible region, the computational complexity of integration becomes insurmountable.

Formulation of reliability problems based on theory of RF is more correct than the quasi-static (based on RV theory). However, its solution requires knowledge of the correlation functions or spectral density functions of the loading process, by which the structure condition parameters are described, and its capacity is calculated.

The *mainstream approach* to structural reliability problems using the RV theory started after the well-known work of A. Freidental [149] when all the random "input" parameters of the problem were normalized, using specific mathematical methods. This normalization is done by transforming all non-Gaussian PDFs into "equivalent"

Gaussian PDFs using various mathematical transformations which, obviously, add some unknown errors into the final result. At the same time, physical interpretation of the problem becomes difficult and its transparency is lost immediately. The next step in solving this problem is constructing the limit state surface (SLS) in the space of multidimensional normalized parameters, which in itself is a nontrivial mathematical problem. SLS may be a linear or nonlinear multidimensional surface. In the latter case it is linearized. Then the minimum distance from the origin of coordinates to the limit state surface is found which, in its turn, requires application of various, quite complex optimization procedures. If the number of the problems parameters is larger than three, the problem becomes hard to visualize and, in addition, requires multiple solutions, to make sure that a global, not local, minimum was found. This minimal distance from the origin to SLS would be the system reliability factor, and is expressed in a number of standards. The linearized reliability assessment algorithm received an abbreviation FORM (First-order reliability method), FOSM (First-order second moment), and the nonlinear algorithm is known as SORM (Second-order reliability method). From the description of this approach, it can be seen that it uses sophisticated mathematical methods with unverified accuracy of results, which is hard to visualize. It should also be noted that up to now no methods existed which would, theoretically, give absolutely correct POF assessments.

A practical method of reliability assessment should have the following traits: it should allow accounting for a large number (>5) of RVs in the nonlinear limit state equation, be physically transparent, algorithmically relatively simple and reasonably fast, and produce verifiable and defendable results. In this context, the FORM methods are not suitable as they do not account for the nonlinearity of the limit state function and give only rough reliability estimates. The SORM methods do account for the nonlinearity, but are quite algorithmically complex, especially when a large number of RVs have to be taken into consideration, and physically not transparent, because they involve a sequence of complex mathematical procedures, each of which takes the problem farther away from physical reality. The results are also hard to verify, because the algorithm involves an optimization procedure which seeks the minimal distance of the design point from the origin in a multidimensional nonlinear space. The problem may have several minima and it is not clear, whether the optimization procedure found the actual "*minimum minimorum*" [150]. For real-life cases this method is also very computer time consuming and not quite fit for producing mass calculations.

In this context, research along the way using direct identical transformations of the actual PDF, which reflect real essence of this or that parameter [2, 5, 10, 20, 22, 151], became an alternative to the above method.

It should be noted, however, that the maturity of both described approaches is yet insufficient for confident practical assessment of the complex systems reliability. A reason for this is the lack of methods, algorithms, and programs which would allow direct accounting for a large number of random parameters (>6–7), which is a must for obtaining accurate reliability and probability of failure assessments of real-life large-scale mechanical systems.

The second approach to pipelines reliability assessment based on the RF theory employed representation of a force impact on a pipe in the form of differentiable stationary (homogeneous) Gaussian functions of time (V.V. Bolotin, B.P. Makarov, V.P. Chirkov, G.Kh. Murkhazanov et al.) which, however, inadequately describe the actual impact on the pipe with the exception of, probably, operating pressure fluctuations. Use of this load and impact representation requires availability of a significant volume of input information, which may be obtained only on the basis of continuous monitoring of the structure. The contemporary state of the problem is characterized by the deficit of statistical data about load parameters changing in time. In addition, this kind of representation of loads does not permit evaluation of the probability of exceeding low levels of loads, which is necessary for solving the reliability problem under a combination of vector loads applied to a pipe. At the same time the problem about combination of loads is the basic one.

In [144] a method to solve this kind of problem is proposed, by representing loads as Markov processes of birth and death (discrete states, continuous time), and diffusion Markov processes. This kind of description allows getting an ultimate solution of the problem of combination of loads on a designed mechanical system in the space of loads and impacts.

Pipeline material properties (tensile strength and yield strength of both the main pipe material and the weld) have been long time recognized as random values. Processing of a large volume of statistical data on steels, produced by metallurgical plants worldwide, demonstrates that the distributions of the said parameters are very well described by a normal law [20]. In practice, normal distribution is the most commonly used. This is explained primarily by the fact that it is the simplest and most convenient distribution allowing using in calculations the table values of normal PDF and its integral.

This book presents an updated version of the well-known method of reliability assessment based on expansion of the limit state distribution function in Gram–Charlier–Edgeworth series, as applied to a defective pipeline segment with defects. It is normalized in a way that the expansion is a genuine PDF, and has the ability to account for the nonlinearity of the limit state function (LSF) and for avoiding negative probability values in the tail areas of non-Gaussian distributions (which sometimes takes place).

This allows accounting for any required number of LSF moments and for the majority of cases. The proposed method accounts for the random nature of pipeline parameters, defects, and loads. G–C–E expansion is built on the first four LSF distribution moments. For the initial data (pipe parameters, defects size, load, and mechanical properties of material) various PDFs are used: uniform, normal, logarithmically normal, exponential, Weibull or Rayleigh, which allow satisfactory description of, practically, any statistical data encountered in practice.

As was mentioned before, one of the main causes of pipeline systems failure is the existence of a large number of actively growing defects of various types. A classic approach of structural reliability theory—representation of a system in the form of connected in series elements [10] (defective cross sections)—is poorly applicable in real life. When this calculation approach is used, the probability of faultless operation of the whole system equals to the product of faultless operation probabilities of all its elements. Reliability parameters of this type of system are lower than the respective parameters of its elements, and with the growth of the number of elements (defects) there is a dramatic decrease of the system reliability. If the number of elements m of the system is significant, it becomes practically impossible to build a system with the required (high) reliability factor. For instance, if *m* is significant, it becomes practically impossible to build a system with the required (high) reliability factor. For instance, at $m = 10^3$ and assuming each element reliability $P_0 = 0.9999$ (probability of failure equals 10^{-4}), reliability of the whole system would equal $P = 0.9999^{1000} \approx 0.91$, then the whole system POF equals $0.089 > 10^{-4}$. Hence, the average life time of such a system is 103 times shorter than the average life time of each element. The main cause of this is that in the chain model all defects are involved in the POF calculation and essentially influence its value. But, in distributed pipeline systems not all the defects present are capable of creating an input into its POF.

To account for this circumstance it was suggested to take into consideration only "significant" defects which can actually affect the system reliability. At the same time there are no recommendations on to how to select the "significant" defects. Practically, to select from the entire set of defects, those which possess this quality, it is necessary to perform fairly complex calculations.

In this book PS degradation—decrease of its residual strength (failure pressure) is described by a nonhomogeneous Markov pure death process, and corrosion defects growth—by a Markov pure birth process, both with a discrete number of states and continuous time. This allowed studying joint behavior of a large number of actively growing defects in a pipeline as in a *distributed system* and eliminating the deficiency of the classic structural reliability theory approach.

Description of corrosion defects growth detected in a pipeline segment, and the degradation (residual strength decrease) of this segment by Markov pure birth and pure death processes, respectively, allowed determining the conditional probabilities of its failure by the leak and the burst criteria under combined action of operating pressure and active growth of the pipe wall defects. This approach makes it possible to calculate the optimal time for the next inspection or maintenance of a defective pipe segment.

An approach to mechanical systems reliability assessment using the random processes theory based on representing loads as Markov processes of birth and death (discrete states, continuous time) and diffusion Markov processes (continuous states, continuous time) was proposed in 1978–1979 by S.A. Timashev [144] and applied for assessing reliability of frames and shell systems under a combination of random loads.

Markov chains are used in [152] for describing cumulative damage in the form of fatigue cracks and wear in structures and its elements, using the so-called B-models. In [153] and [119] the theory of Markov models was applied to assess the state of high-pressure pipelines. In [153] the growth of corrosion pittings is considered as a Markov chain. In [119] a Markov chain in the form of the Yule model was chosen for consideration because it is the simplest model, which operates with only one transition intensity.

However, Markov processes (with a discrete number of states and continuous time) are more universal and adequately describe the true state of thin-walled pipeline systems. Markov processes are described by systems of differential equations and do not depend on the nature of objects and their physical properties. In this sense, they are universal and are widely and successfully used in various fields of science and technology: nuclear physics, biology, astronomy, queueing theory, reliability theory, etc. [10, 144, 152, 154–157]. Unlike Markov chains, they permit assessment of the probability of finding the system in each of the states and the intensity of transition from one state to another at any time.

Examination of literature shows [158–161] that there are no studies on the construction of such Markov models as a pure birth (death) Markov process which describes the degradation of the bearing capacity of a distributed system with a finite set of discrete defects. In order to use these processes, the transition probabilities must not depend on the past, and the sojourn time for a process to be in any particular state should be exponentially distributed. Multiple empirical studies show [158–161] that both conditions take place in most types of technical systems, including pipelines. Assessment of reliability of such systems usually is based on an exponential distribution of pipeline defective cross sections uptime, and does not depend on the previous time of safe operation.

2.7 Reliability Level Embedded in Pipeline Design Codes

Two main principles are currently used for structural design: the operating-stress design method and the limit state method. The operating-stress design (OSD) method [162] is based on the rule that the dimensions of structural elements are defined subject to the condition that the operating stresses in them should not exceed allowable stresses, understood as a certain portion of the material tensile strength limit. The ratio of tensile strength to allowable stress is called a safety factor. The assigned values of this factor did not have sufficient scientific background. In addition, the allowable stresses themselves make sense only when assuming proportionality between the active load and stresses right up to destruction, which, as is known, takes place only on rare occasions [162]. In pipeline design codes [112, 114–117] the OSD method is used [43].

The Russian code [163, 164] prescribes that pipeline design be done using the limit state method [5, 43, 162, 165]. The limit state method is a modern method for designing civil engineering structures, which belongs to the group of semi-probability methods, since it relies on statistical methods for justification of the selected codified safety factors using quantiles of a certain level. A distinctive feature of the limit state method as compared to the operating-stress design method, apart from its universality, is the introduction of several limit states, which limit operation of the structure, and a new system of design factors (overload, homogeneity, and operation conditions), instead of a single safety factor [162].

Three types of limit states are distinguished:

1. *bearing capacity limit state* (strength and stability of structures, material fatigue), upon reaching of which the structure or its element loses ability to further resist the external impact, or accumulates such residual deformation, which makes its further operation impossible;
2. *excessive deformations limit state* of structures under static and dynamic loads, upon reaching of which a structure, otherwise maintaining strength and stability, is not able to continue to operate safely, due to appearance of excessive deformations or vibrations;
3. *crack formation or crack opening limit state*. Upon appearance and opening of cracks in a structure (which maintains its strength and stability) to the extent, which makes its further operation impossible/impractical, due to loss of the required tightness/integrity, danger of corrosion, or the lining damage.

The root idea and the final goal of structural design using the limit state method is obtaining sufficient guarantees that over the period of the structure operation none of the inadmissible limit states will occur, either for the structure as a whole or for its individual elements.

The ability of reaching any of the structure limit states depends on many factors, the most important of which are the following:

- external loads and impacts;
- quality and mechanical properties of structure materials;
- general conditions of manufacturing, operating the structure, etc.

The main pipelines limit state design method was originally developed by the "*VNIIST*" team of research engineers *I.P. Petrov*, *A.G. Kamerstein*, *V.S. Turkin*, et al. Main pipelines design codes [164] are based on this methodology. The essence of the method is consideration of such a stress and strain state of a pipeline which makes its further operation impossible.

According to [164], the pipeline-bearing capacity is characterized by the ultimate tensile strength of pipe metal. To ensure safe pipeline operation, when defining the value of the design strength, several partial reliability factors are introduced: reliability factor for pipe material, reliability factor for pipe operation conditions, and safety factor which takes into account the pipeline purpose of existence.

In [164] the first limit state is written in the form of an equation in which the tensile hoop and tensile axial longitudinal stresses are equaled to the design pipe material strength. For the case of tensile/compressive stress state the equivalent stresses are equal to the design strength.

To limit plastic deformations in the pipeline, the second limit state is provided. This state is expressed via stresses in the most stressed point of the pipe section, which are defined from all characteristic loads and impacts (taking into account their combinations). A criterion of reaching the second limit state is the condition under which the hoop and tensile axial stresses, or the equivalent stresses, are equal to the pipe metal yield strength. Standard [164] does not account for the presence of various types of defects in operating pipelines, and all calculations are performed for ideal pipes without defects

Industry guidelines and companies' standards [30, 41, 166–168], which have, in fact, only status of recommendations, are just interpretations and some modifications of the method [114]. In these standards certain safety factors were changed, or additional ones introduced, as a reflection of pipelines construction and operation specifics. A comparative analysis of main pipelines design methods according to codes of different countries is provided in [162].

From the moment of the first introduction of codes [112, 114–117], in the early 1980s and to this day, their development was and still is focused exclusively on experimental updating of their empirical parameters and factors. However, the underlying basis of all "modified" design formulas is the criterion of plastic fracture (2.1) and the formula (2.2), which expresses the dependence of hoop stress in a linear elastic thin-walled cylindrical shell of ideal shape on the inner pressure [120, 121].

Deterministic methods for calculating residual strength of pipeline segments [112, 114–117] do not account for the random nature of pipeline geometry (wall thickness, diameter, and possible dent sizes), properties of the pipe material (yield and ultimate strength), loads and impacts (changes of operating pressure), the presence of a significant number of stochastically growing in time defects of various natures, and uncertainty of their dimensions because of the ME made during pipeline inspection. The main purpose of these methods is to provide a design tool which would be as simple as possible and require minimum amount of input data for calculation.

To compensate for the random nature of loading, pipeline geometry, material properties, as well as errors during construction, and operation of pipelines, the developers of various semi-empirical methodologies introduce large safety coefficients. In the course of practical application of these methods, this (often excessive) conservatism becomes obvious, when they lead to severely underestimated failure pressure values, which, in their own right, lead to over rejection of defective pipeline segments, significant reconstruction-related material costs, and a substantial decrease of the pipeline transportation capacity. However, this conservatism of methods [112, 114] does not make them less used. JSC "*Gasprom*," while using [30, 41, 168, 169], in order to account for national specifics, on the contrary, introduced additional safety factors into the design expressions of method [114].

Comparison of calculation results obtained for the modified criteria [114], with the actual field tests data gleaned from pipelines with corrosion defects, indicates that the methodology [114] is excessively conservative. This was repeatedly noted by specialists involved in the operation of commercial PS and employing method [114] (and the like) for assessing residual strength of the defective segments.

Thus, comparison of the hydro-testing data of 92 corrosion affected segments of the "*TNG*" (Argentina) with the results of calculations using modified criteria [114] shows that the experimental burst pressure values, in practically all cases, were 1.3–1.7 times higher than the estimated ones [118]. According to the data of JSC "*Orenburg Gasprom*" [170], analysis of failed pipes damaged by corrosion demonstrated that the actual burst pressure was, on average, 1.2–1.5 times higher than the design pressure calculated using the modified criteria [114].

Thus the deterministic criteria do not account for many factors contributing to the PS POF probability of failure (reliability) value. To eliminate this problem it is necessary to use probabilistic models, which account for the random nature of their parameters and loading.

However, in this case another problem appears. The regulatory documents used in various industries and countries for the highly critical structures, including oil pipelines, establish quite low admissible failure probability (emergency situations) values: for accident with disastrous consequences—10^{-6}, for major (critical) accidents—10^{-4}–10^{-6}. When the probability of failure is low, it is necessary to evaluate the real reliability level which is embedded in the PS design methods. The calculated in such a way probabilities may be interpreted as some analogs of safety factors initially built into the design methodology, and more informative than the strength factor in a deterministic formulation.

It is also important to know how sensitive are the design codes for pipelines with defects to the random nature of certain parameters covered by these methodologies. Such parameters are pipeline geometry parameters (web thickness and diameter), properties of the pipe material (yield and ultimate strength), loading (operating pressure), and the defect parameters (depth and length). This type of analysis allows understanding which of the parameters of a pipeline system with defects are the most critical for its reliability. The reliability embedded into the design of a pipeline with a single defect was studied in [171].

2.8 Entropy of Degrading Pipeline Systems

Any information about a physical/engineering system (machine, apparatus, structure, or infrastructure) is complex and usually contains sets of different types of data about the object. If monitoring and/or diagnostics of such a system is conducted, its operator receives, continuously or intermittently, reports on its current condition. The data being received would be meaningful only if the current state of the system is not known in advance. This is the case for engineering systems, which are subjected to different forces and influences of random nature, and are comprised of materials which change their physical properties over time in a stochastic manner. Therefore, its physical state is randomly changing over time.

Consider an engineering system (say, a pipeline), which is continuously monitored, and the information about the current state of the system and its elements and components is fed to a decision maker (DM). Obviously, the utility of the gleaned information is more valuable for the DM, the greater is the uncertainty of the current system state. Here a natural question arises: What does "more" or "less" of uncertainty degree mean, and how it can be measured?

In physics and the probability theory a specific measure of uncertainty is used, namely the *entropy* [108, 153, 172–177].

Entropy (from ancient Greek "turn," "transformation") in science in general is a measure of disorder of a system consisting of numerous elements. Entropy is one of the most important concepts of physics. The word “entropy” was first used in 1864 by Rudolf Clausius in his book “Abhandlungen Fiber die Warmetheorie” (“Works on the Theory of Heat”) as a notation of the quantity that characterizes the process of converting thermal energy into mechanical energy.

In 1877 Ludwig Boltzmann established a relationship between entropy and probability of the system being in a particular state. Later, this relationship was utilized in the Max Planck formula (postulate). Albert Einstein called it the Boltzmann’s principle, and with it the statistical mechanics began. Boltzmann’s principle allowed going beyond the equilibrium of thermodynamics and statistical physics, into other areas of science, including information theory.

Shannon continued and developed the principles of Boltzmann statistical thermodynamics and in his works used entropy as an index of uncertainty in information theory [176, 178], assuming that an increment of information equals the lost uncertainty value. Therefore, the amount of acquired information may be measured by the quantity of lost uncertainty, i.e., entropy.

Shannon’s definition of entropy was related to the notion of thermodynamic entropy. There is a relationship between the thermodynamics and the information entropy—a profound similarity of mathematical tools of these two fields up to complete identity of formulas (e.g., for discrete random values entropy). Application of the information entropy concept in various fields of knowledge and technology proved to be quite effective.

The research potential of entropy concept is far from being exhausted by the existing applications. In perspective, the entropy approach may be taken up by a new scientific research discipline—synergetics, which focuses on the study of the regularities of the formation and disintegration of space-time structures in systems of various types: physical, chemical, biological, economical, social, etc. [174].

In [179] a problem of using entropy for studying large structural systems is discussed. However, so far there are practically no studies on the quantitative use of the concept of entropy for analyzing processes of degradation of machines, equipment, and structures.

This book describes an example of practical application of the entropy concept as an integral index of structural damage of structures, with pipelines chosen as a meaningful example. This approach may be used for the study of other structures’ and machines’ behavior.

2.9 Prediction of Fracture and Assessment of Pipelines State Subjected to SCC

A significant part of worldwide main gas pipelines is located in the waterlogged soil environment. This contributes to stress corrosion cracking which is a serious problem for the gas industry [180–183]. worldwide. SCC-type defects are characterized by the presence of spots, consisting of hundreds of surface longitudinal cracks, which may merge, forming extended surface defects [180, 183]. A typical defect length to depth ratio of a SC crack is 50–200 [184]. An environment responsible for SCC is most often a carbonate–bicarbonate solution [180].

Identification and characterization of corrosion damage areas is performed with the use of various nondestructive control methods. If, as a result of inspection, a SCC-type defect is detected, it is necessary to evaluate its effect on the remaining life of a pipeline in order to define priority actions required to maintain its integrity (continue operation, conduct repair, or replacement of a defective segment) [184].

Surface defect depth is usually approximated by a semi-ellipse. In the case when there is a series of defect depth sizes along its length, the corresponding (effective) defect area is determined in the longitudinal cross section of the pipeline. The worst defect is approximated by an equivalent semi-ellipse [60, 184]. In the absence of these data the maximum depth and length of a defect are considered. Frequent pipeline failures under the SCC conditions give evidence of the need to develop a failure model, which may be used for assessing safety and integrity of pipelines operation.

The main scheme of prognosis and assessment of pipelines state under SCC conditions has been discussed in [184, 185]. The following main stages are identified:

- determine geometric parameters of a corrosion defect (its initial size);
- select the failure criterion;
- conduct prognosis of the defect critical size, which will cause pipe failure;
- calculate the remaining life of a pipeline segment by accounting for the stress corrosion defect growth.

In this book, a solution is described of evaluating remaining life of a pipe segment with longitudinally oriented external stress corrosion crack, subjected to cyclical load impact. An algorithm is proposed to assess the remaining life of a pipeline with SCC-type cracks by the crack growth criterion, using nonlinear failure mechanics. Examples are provided of calculations for a main pipeline segment with a single (maximal) and multiple SCC-type cracks, taking into account their interaction. Application of the more efficient (as compared to the statistical testing Monte Carlo method) adaptive important sampling method for assessing reliability of pipelines with SCC-type cracks is demonstrated, including an algorithm for updating reliability of a pipeline segment under the SCC conditions for three different outcomes of the segment inspection.

An updating algorithm is proposed, which employs a Bayesian network for assessing pipeline reliability and the distribution characteristics of its random parameters, taking into account new information (received as a result of inspection) of pipe condition and its individual segments. Cases of series and parallel connections of pipe segments are studied.

2.10 Predictive Maintenance of Pipeline Systems with Defects

Maintenance is a combination of organizational and technical actions taken for maintaining operability and integrity of a pipeline (as an element of a complex system) in the process of its operation, including monitoring of its state, risk management, etc.

The main principles of critical systems maintenance aimed at ensuring their safety and integrity are described in [144, 186–188].

According to the proactive maintenance principle for potentially hazardous assets and structures, including pipelines, the category of "conditional limit states" may cover conditions, realization of which does not necessarily require cessation of their operation/use for intended purpose or their decommissioning. The so-called "warning" and "critical" failures do not lead to accidents, since they are conditional failures, and are introduced out of various engineering considerations, only to fixate the moment of occurrence of some specific states of an object, which "trigger" certain maintenance actions, necessary for keeping the system in operational condition (e.g., diagnostics, repair, operating pressure relief, etc.). When reaching these states, the operability of a structure is not compromised. However, future operation of the object may involve a significant increase of the risk of real failure occurrence.

These states serve as the "levels," which trigger some actions, aimed at renewal of the object, or at preserving the current condition of the asset. These levels are then optimized by solving the problem of multilevel policy control of infrastructure failure probability. Defining the time of occurrence of these conditional failures is the key for ensuring safety and integrity of PS operation.

Significant attention is being paid to the problem of calculating PS remaining life before a critical or limit state occurred [4, 10, 108, 145, 169].

The remaining life is a *conditional random time* of transition of a pipeline segment from the current state into a critical or limit state. RL is a random value, since it is dependent on many random parameters, and is based on a multitude of constraints and rules introduced into the operational characteristics of a pipeline.

Knowledge of the remaining time till the occurrence of a certain warning, critical, or limit state allows optimization of PS maintenance and repair costs, without creating unjustified risks for its integrity, and making informed management decisions about selection of a critical or limit state criterion to be used in a particular situation.

Analysis of industry standards, as well as literature on the subject, revealed that in practice in a majority of cases the RL assessment is based on two deterministic failure criteria: "leak" and "rupture," and the shortest remaining life time is selected. Time of reaching the critical state by a "leak" criterion is defined as the time required for a defect under the estimated corrosion rate to reach the depth of 60, 70, or 80 % of the pipe wall thickness (depending on the code used). Semi-empirical codes [112], B31Gmod [114], Shell92 [117], DNV [115], and PCORRC [116] are used, as a rule, for evaluating residual strength (burst pressure).

Obviously, when assessing the pipeline RL, possible types of conditional failures must be taken into account, which would allow predicting, with sufficient accuracy, full evolution of the PS state, up to the moment of its physical failure.

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