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Probabilistic Analysis of Transportation Systems for Oil and Natural Gas

Yuriy V. Lisin, Nikolay A. Makhutov,
Vladimir A. Nadein and Dmitriy A. Neganov

Additional information is available at the end of the chapter

Abstract

In this chapter, the need of probabilistic modeling for design, construction, and operation of oil and gas pipelines is justified. Such modeling should use information and databases on deterministic and statistical dependencies related to deformation, damage accumulation, failure, fracture accidents, and catastrophes. The probabilistic design equations and their parameters for the characteristics of strength, durability, fracture toughness, risks of accidents, and manmade catastrophes are given. The economic efficiency of pipeline management based on controlling probabilistic characteristics through conducting diagnostic, repair-and-renewal operations while ensuring the acceptable levels of reliability and safety parameters is substantiated. The results of studies in the field of statistics and probabilities of emergency situations during manufacturing, construction, and operation conducted by Russian and foreign specialists are presented.

Keywords: oil and gas transportation, pipeline transport, main pipelines system, pipe steel, pipeline strength, yield strength

1. Introduction

Oil, gas and chemical complex (OGCC) is one of the system and fund forming in our country. It includes tens of thousands of oil and gas production facilities, over 500,000 km of field and main pipelines for transportation of liquid and gaseous hydrocarbons, thousands of large oil and gas storage facilities, and hundreds of major oil and gas refineries for fuel and chemical products for civil and military use.

These figures indicate the exceptional importance of the integrated safety and security of the national oil, gas, and chemical complex, which constitute a significant part of the national and international safety problems. The scientific analysis of these problems, and the solution of fundamental, practical and economically significant tasks in the field of safety are becoming more relevant as the scope and geography of OGCC expands in Russia.

In the second half of the twentieth century and the beginning of the twenty-first century, environmental and economic damage, accidents, and injuries at the facilities of the OGCC (including objects of the main pipeline systems (MPS)) became the subject of active interaction between state authorities, sectorial scientists, and design, technological, construction, and operating organizations. The leading roles in this interaction belong to the Security Council, Rostekhnadzor, the Russian Academy of Sciences, the research centers of the largest companies (Transneft, Gazprom, Rosneft), and the leading universities in the country.

In the traditional and advanced safety developments for OGCC and MPS facilities, the priority will be under scientifically grounded combination of research, rationale, regulation, and expertise, as well as improvement of strength, durability, and safety of the technologies in the light of the emerging spectrum of threats and risks in the context of diversifying economy.

The solution of these problems mainly lies in deterministic, statistical, and probabilistic methods of modeling, calculations, tests, and justification of performance of OGCC and MPS facilities.

Therefore, the major focus is on the probabilistic, statistical, and deterministic analysis of strength and durability of the main pipelines for oil and gas transportation.

2. Basic design dependencies

In the second half of the twentieth century and the beginning of the twenty-first century in Russia and abroad, branched pipeline systems for hydrocarbons transportation, including the main and field oil and gas product pipelines have been constructed. At present, one of the world's largest pipeline systems operates in Russia (**Table 1**) with a total length of more than 500,000 km.

Design, construction, and operation of pipelines for many decades were based [1–5] mainly on the strength standards. These standards (in the form of state standards (GOST), industry standards (OST), building norms and rules (SNiP), guidelines (RD), technical regulations (TR), federal rules and regulations (FNiP), methodological recommendations (MR)) were based on:

- Classical strength theories (I) maximum normal stresses σ_{max} (II) maximum deformations e_{max} (III) maximum tangential stresses τ_{max} (IV) maximum forming energy V_{max}

- Analysis of designed operational nominal stresses σ_n^3 by methods of material resistance and the theory of rods, plates, and shells

No.	Type	Purpose	Length (ths. km)
1	Main pipelines	Gas pipelines	180.2
		Oil pipelines	55.3
		Product pipelines include: Ammonia pipelines NGL pipelines	22.2 1.4 4.3
		Total	**257.8**
2	Field pipelines	General purpose	250.0
Total			**507.2**

Table 1. Types, purposes, and length of pipeline systems.

- Use of the calculations of allowable stresses $[\sigma]$ or limiting resistances R_u

- Basic characteristics of the mechanical properties of pipe steels that determine the resistance to plastic deformation, failure, and loss of stability

Generally, the conditions of pipeline's strength, at present, can be described (**Figure 1**) [1–3] by the functional relation:

$$\sigma^s_{n\,max} = F_\sigma\{p, N, M_u, M_k, \delta, D, E, R_u, \mu\} \leq [\sigma] = \frac{\sigma_{on}}{n_\sigma},$$

$$\sigma_{on} \leq F_o\{\sigma_{max}, \varepsilon_{max}, \tau_{max}, V_{max}\} = F_\sigma\{\sigma_{\text{т}}, \sigma_{\text{в}}, \sigma_y\}$$

$$(1)$$

where $\sigma^s_{n\,max}$—maximum designed stress for the most dangerous operating conditions (taking into account internal and external pressure p, axial forces N, bending M_u, and torque M_k in a critical section and a critical point); σ_{on}—critical (ultimate) stress, determined from the test
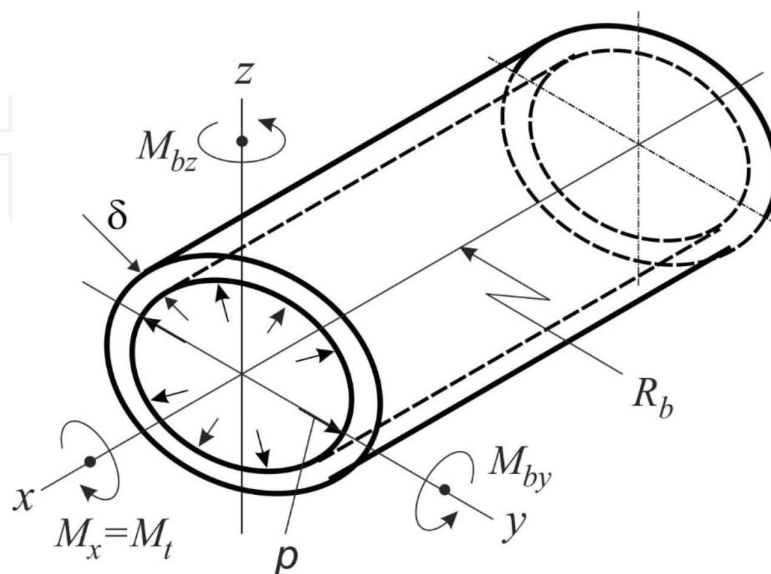

Figure 1. Scheme of operational loading of the pipeline.

data of standard specimens on strain (compression) at the stages of the beginning of fluidity (yield point σ_y), reaching the ultimate strength (ultimate stress limit σ_u) or the beginning of buckling (critical stress σ_y); $N = N_x$—longitudinal force along the x-axis; M_{6y}, M_{6t}, M_{uz}—bending moments around the y- and z-axes; $M_t = M_x$—torque around the x axis; n_σ—margin of safety ($n_\sigma \geq 1$); δ—pipeline wall thickness; D—diameter of the pipeline (external, internal, or mean); E—modulus of longitudinal elasticity; μ—Poisson's ratio; and R_6—bend radius of the pipeline axis.

All the calculated parameters of Eq. (1) can be considered in deterministic, statistical, and probabilistic formulation, taking into account the complication of operational conditions and the improvement of engineering methods of mathematical modeling, physical experimentation, and normative calculations.

The calculation of stresses $\sigma^s_{n\,\max}$ as a function F_σ in Eq. (1) is the initial independent goal of solving boundary value problems—analysis of nominal stress-strain states under complex operational and exploitational loading regimes at all stages of the life cycle of pipes and pipelines.

In expression (1), based on the static tension diagram of a standard sample (**Figure 2**) in the conditional coordinates «$\sigma - e$» (without taking into account the reduction in the cross-sectional area and increasing the sample length), as critical stress σ_{on} is used [3–5]

- In the yield zone: the yield strength σ_y as the ultimate resistance to elastic deformation—the limit of proportionality σ_p, the yield strength σ_y at the yield plateau, the conditional yield strength corresponding to the achievement of a given plastic deformation, for example, 0.2% ($\sigma_{0,2}$), or a specified elastoplastic deformation, for example, 0.5 ($\sigma_{0,5}$) or 1% ($\sigma_{1,0}$)
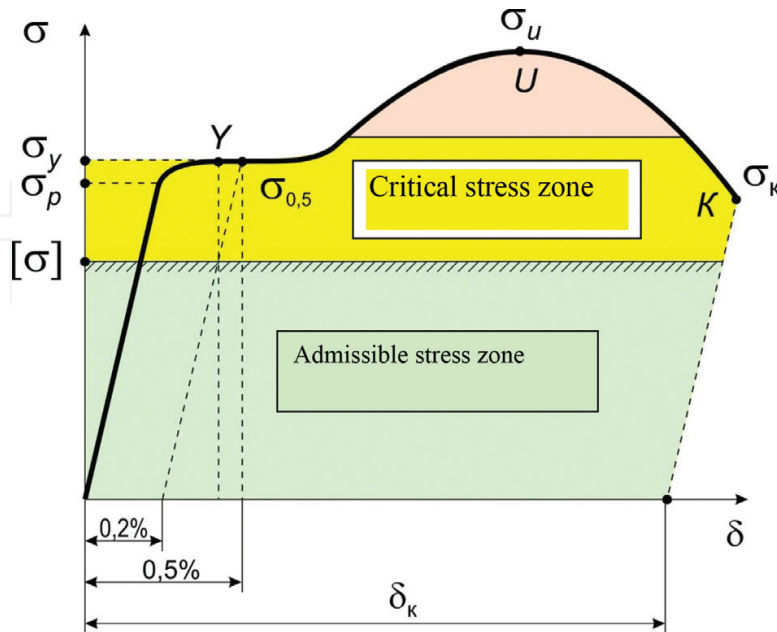

Figure 2. Static tension diagram of a standard sample.

- In the ultimate stress zone: ultimate strength-ultimate resistance σ_u as the maximum engineering stress at the stage of uniformity loss of plastic deformations and neck formation under tension

The calculated plastic (e_p = 0.2%) and elastoplastic deformations (e = 0.5% and e = 1%) for modern tube steels are substantially smaller than the relative elongation δ_κ in case of failure. In this connection, for tube steels $\sigma_p \leq \sigma_y \leq \sigma_{0,2} \leq \sigma_{0,5} \leq \sigma_{1,0}$.

Introduction to calculation (1) stresses σ_{on} in the form of the above characteristics makes it possible to exclude the appearance of mechanical properties of three dangerous limit states:

- Beginning of fluidity and formation of plastic deformations ($\sigma_p, \sigma_y, \sigma_{0,2}, \sigma_{0,5}, \sigma_{1,0}$).

- Failure after reaching the ultimate strength (σ_u).

- Total loss of stability after reaching critical stresses.

This required the use of three safety margins n_u:

- Yield strength n_y.

- Tensile strength n_u.

- Critical stress σ_c under loss of stability n_c.

Hence, in accordance with Eq. (1), the allowable stress $[\sigma]$ must be minimal:

$$[\sigma] = \min\left\{ \frac{\sigma_y}{n_y}, \frac{\sigma_u, \sigma_c}{n_u, n_c} \right\} \tag{2}$$

Since for the first two limiting states $\sigma_y \leq \sigma_u$ for tube steels hardening in the elastoplastic range, then safety margins are $n_y \leq n_u$.

According to the third limiting state, there are two possible cases:

If $\sigma_c \leq \sigma_{\text{в}}$ then $n_c \leq n_u$.

If $\sigma_c \leq \sigma_y$ then $n_c \leq n_y$.

When calculating pipeline's strength in limiting states in accordance with national standards and when the design resistances R_y (inadmissibility of plastic deformation development) and R_u (inadmissibility of destruction) are used, then

$$[\sigma] = \min\left\{ \frac{R_y \cdot m\psi}{n \cdot K_2 \cdot K_{\text{н}}}, \frac{R_u \cdot m\psi}{n \cdot K_1 \cdot K_{\text{н}}} \right\} \tag{3}$$

where m—condition load effect factor; $K_{\text{н}}$—design safety factor; n—load safety factor; K_1, K_2—material resistance factor; and ψ—factor for biaxial stress states.

№.	Factor	Symbol	Value
1.	Condition load effect factor	m	0.6–0.9
2.	Load reliability factor	K_1	1.1–1.5
3.	Material resistance factor	K_2	1.34–1.55
4.	Design safety factor	$K_н$	1.0–1.05

Table 2. Calculated normative values of factors.

From Eqs. (2) and (3), it follows that margins n_y and n_u in the calculations for the allowed stresses are related to the factors m, K1, K2, and Kн, in Eq. (3) for calculations on the limiting states at $R_y = \sigma_y$ and $R_u = \sigma_u$:

$$n_y = \frac{K_2 \cdot K_н}{\psi m}, \quad n_u = \frac{n \cdot K_1 \cdot K_н}{\psi m} \tag{4}$$

In essence, the safety margins n_y, n_u and stability n_c according to Eqs. (2)–(4) reflect the role of statistical and probabilistic uncertainties, inaccuracies, ignorance, and responsibility of pipeline systems.

Based on strength and stability calculations under Eq. (1) with addition of Eqs. (2) and (3) for the pipeline with given p, N, $M_в$, M_t, $R_в$, and D, the wall thickness δ is chosen to be greater than the minimum ratio of yield strength σ_y and strength σ_u to margins n_y and n_u with subsequent binding of stability with σ_c and n_c.

Equation (2) defines the area of allowable stresses for deterministic normative calculations of pipeline strength (**Figure 1**).

The values of the factors in the calculations according to the norms [2] are given in **Table 2**.

3. Trends in improving methods of rationing, calculation, and management of mechanical properties of pipe steels

In the evolution (τ) of pipeline transport in Russia and abroad, three trends have been and are currently dominant (**Figure 3**) in view of Eqs. (1)–(4) in deterministic formulation [3–7]:

- Increase of the diameter of pipelines D (from 250–300 to 1200–1400 mm) and pressures p (from 2.0–2.5 to 14.0–16.0 MPa)

- Increase of mechanical properties of pipe steels (yield strength σ_y) (from 200–250 to 600–800 MPa) and strength σ_u (from 400–450 to 700–900 MPa)

- Decrease in safety margins n_y (from 1.8–3.2 to 1.2–1.5) and n_u (from 2.4–3.5 to 1.6–1.8)

At the first stages (1930–1960) of the development of pipeline systems, carbon (with a carbon content of 0.22–0.35%), unalloyed steels with larger of the abovementioned margins n_y and n_u,
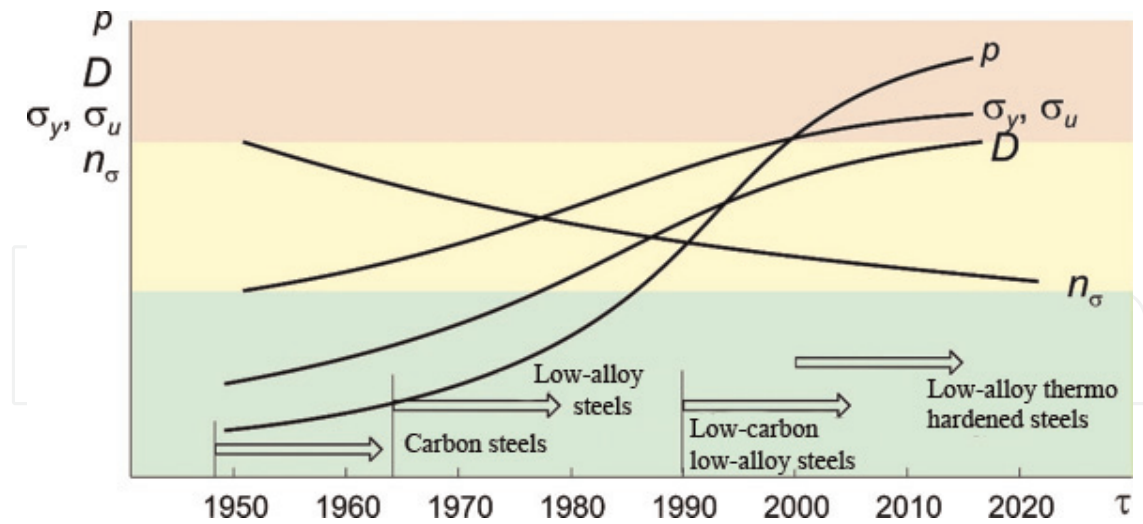
Figure 3. Basic determinate variations in design parameters of pipelines.

and lesser p, D, σ_y, and σ_u were predominantly used. Under these conditions, when determining the thickness of the pipe wall δ, the margins n_y and yield strength σ_y proved to be key factors, because they gave smaller permissible stresses $[\sigma]$ under Eqs. (2) and (3).

The idea that increasing the pipe steels yield strength σ_y is crucial in those years led to the desire of metal scientists, technologists, and designers to reduce the material consumption of pipelines by increasing the yield strength σ_y by all available methods and means (alloying steels, thermomechanical processing of sheets and pipes while reducing margins n_y). The same approach was typical for the development of general engineering, energetics, oil and gas chemistry, transport, and construction.

In the process of accelerated development of pipeline systems, low-alloy steels, low-carbon low-alloy steels, and low-alloy thermo-hardened steels have been consistently used since the 1960s.

This aspiration not supported by the necessary scientific justifications led to:

- Significant problems with increased damageability of objects such as pressure vessels and pipelines with high parameters of pressure P and temperature t in thermal power engineering, bearing structures of civil and industrial buildings

- Extended brittle fractures and loss of stability of the main pipelines

From the generalized statistical analysis of damage and destruction of various objects (including those working under increased pressure), it follows that engineering materials, design, and technological solutions associated with increase of σ_y and decrease of n_y are insufficient to prevent large-scale emergency and sometimes catastrophic situations. It became clear that the existing engineering practice of calculation focused on the designation of independent margins n_y and n_u and the basic characteristics of strength σ_y and σ_u is entailed with the danger of a real and reliable operation of pipeline systems.

One of the main problems was a complex, interrelated deterministic, statistical, and probabilistic analysis of the determining parameters—safety margins n_σ, n_y, and n_u and mechanical properties σ_y and σ_u in Eqs. (1)–(4). According to Eqs. (2) and (3), the minimum allowable stresses $[\sigma]$ give the maximum quantitative coherence between these parameters:

$$n_y = n_u \left\{ \sigma_y / \sigma_u \right\} \tag{5}$$

Managing safety margins n_y and n_u for the purpose of their reduction should be carried out in accordance with ratio σ_y/σ_u, which is featuring, as shown on **Figure 1**, the hardening degree (or module) of tubular steels in the elastoplastic range beyond the yield point σ_y. For the majority of actually used pipe steels as they are improved with existing hardening methods, with the growth of σ_y and σ_u, the ratio σ_y/σ_u is increased due to preferential growth of σ_y (**Figure 4**).

In the nomenclature and types of the previously used tube carbon steels (**Figures 1** and **2**) with reduced yield strength σ_y (less than 300 MPa) and a ratio σ_y/σ_u (less than 0.6), the traditional calculations of the yield strength σ_y with margins n_y were of primary importance. With a further increase in the yield strength σ_y and decrease in the safety margin n_y, the calculations for the ultimate strength σ_u with margins $n_в$ have become determinative, in accordance with Eq. (5).

However, in this case, the problem of increasing the danger of stability loss under $\sigma^s = \sigma^c$ and an uncontrolled dangerous transition to large plastic deformations according to Eq. (2) remains, in fact, not explicitly reflected in Eq. (5), due to a reduction in the degree of hardening of steels with a simultaneous increase of σ_y and the ratio σ_y/σ_u. Such conclusion in the framework of modern concepts of strength calculations [1, 3–6] required a gradual transition from calculations in stresses σ to calculations in deformations e. This transition already received not only its scientific justification [6–8] but also its practical implementation in norms
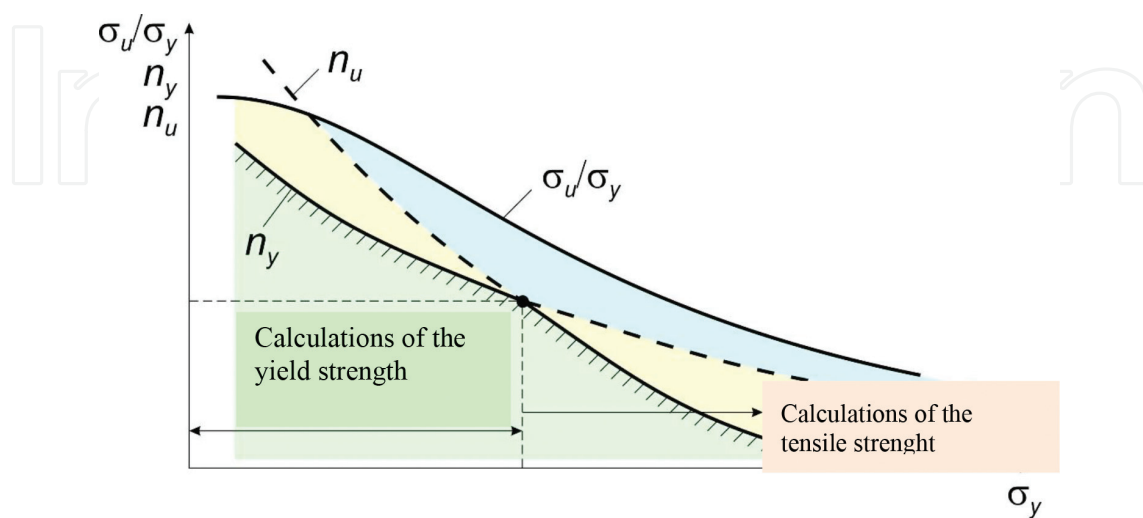

Figure 4. Coherence between strength margins and mechanical properties of pipe steels.

and substantiation of strength of the vessels and pipelines in nuclear reactors [8–10] and space and missile systems [11].

4. Modern problems of justifying the strength of pipeline systems

Four strategic tasks are being solved by methods of deterministic, statistical, and probabilistic modeling and calculation nowadays in Russia:

- Design and construction of new pipelines for liquid and gaseous hydrocarbons transportation (including marine and harsh climatic conditions of Siberia, the North Sea and the Arctic Sea)

- Extension of operation of existing pipelines within the limits of modern regulatory requirements for strength and durability

- Resolving the issues of complex technical diagnostics, repair, and restoration works in the damage areas beyond the norms of permissible defects for the prolongation of safe exploitation within the assigned terms

- Decommissioning in cases of significant exhaustion and formation of dangerous critical and un-repairable defects

The solution of these tasks must meet the modern requirements of:

- The federal legislation on justification and ensuring industrial safety by risk criteria

- Industry norms and rules for justifying strength, durability, and reliability

The tasks of justifying and ensuring industrial safety of pipeline systems in accordance with the criteria of strength, resource, and risks in compliance with the Federal Law No. 116-FZ "On Industrial Safety of Hazardous Production Facilities" are resolved with the coordinating and decisive role of Rostekhnadzor with the participation of the Russian Academy of Sciences, leading oil and gas companies as Transneft, Gazprom, Rosneft, the Russian Union of Oil and Gas Constructors and leading academic and industry institutes and universities.

The main directions of scientific research and applied developments in this direction are reflected in the proceedings of the I and II Forums on industrial safety [12].

The solution of problems of formation and development of industry norms and rules for substantiating the strength, durability, resource, and reliability of pipelines is concentrated in the research institutes of Transneft and Gazprom.

In normative documents [13] that are governing the industry, the following assumptions were made:

- Temporary technological heredity is not explicitly taken into account from the processes of obtaining the parent metal and the production of sheets and pipes in factories and enterprises.

- Mechanical properties (including limits σ_y and σ_u) of structural pipe steels in the process of pipeline transportation, construction, and operation of pipelines are assumed to be unchanged.

- Strength margins n_σ in Eq. (1) and margins n_y and n_u in Eqs. (2), (4), and (5) are accepted unchanged for all stages of the life cycle τ.

- Degradation of pipes and pipelines is associated mainly with a decrease in wall thickness due to corrosion (general and local) and erosion.

- The crucial part in material consumption reduction is in the increase in nominal operating stresses $\sigma_{n\,\max}^s$, yield strength σ_y, and strength σ_u and reduction of margins n_y and n_u according to the Eq. (1).

The normative approach has an important development element in comparison with [2, 13]—in it, the strength and durability evaluation is carried out not only by nominal stresses $\sigma_{n\,\max}^s$ but also by local deformations $e_{\max\,\kappa}^s$ in the concentration zones created by structural, technological, and operational factors (welds, defects, corrosion). This makes the normative calculation of the strength of pipelines comply with both the modern deformation criteria [6, 7] and the norms in nuclear power engineering and rocket and space technology [9–11].

5. Main directions of development of pipeline strength standards

Taking into account parts 1–3, the perspective directions of calculation and experimental analysis of the strength of pipelines in the deterministic interpretation should include:

- Direct quantitative accounting of the degradation and aging in time τ of tube steels at various temperatures t and the number of cycles N, leading to a change in the basic design characteristics—the yield strength $\sigma_\text{т}$ and strength $\sigma_\text{в}$:

$$\left\{\sigma_y(\tau,t,\sigma,e,N),\sigma_u(\tau,t,\sigma,e,N)\right\}=\left\{\sigma_y,\sigma_u\right\}\cdot F_c\left\{\tau,t,\sigma,e,N\right\}, \qquad (6)$$

where $\sigma_\text{y}(\tau,t,\sigma,e,N)$ and $\sigma_u(\tau,t,\sigma,e,N)$—kinetically varying yield and strength limits for a given time τ, temperature t, stress σ, and deformation e; $F_c\{\tau,t,\sigma,e,N\}$—generalized functionals describing the change in the basic mechanical properties under the influence of temperature t, time τ, stress σ, cyclic N, and deformation e factors at all stages of the life cycle of the pipeline.

The functional $F_c\{\tau,t,\sigma,e,N\}$ with its parameters τ, t, σ, e, and N essentially reflects the processes of degradation and aging of pipeline steels in the process of sheet and pipe manufacturing, their transportation, construction, testing, and exploitation of pipelines.

Despite of a huge number of studies in factory laboratories; scientific institutes; design, construction, and operation organizations; and powerful industry research centers, in Russia and

abroad, it has not yet been possible to obtain and justify this functional F_c with the appropriate statistical and probabilistic equations and parameters. The prerequisites for the formation of a system of initial equations for the functional F_c are presented in [4, 8, 11, 13, 14].

Currently, knowledge on the processes of aging and degradation in time τ of carbonaceous and low-alloy steels is reduced to the following basic provisions (**Figure 5**):

- Natural aging (curve 1) of steels in the initial state ($e = \sigma = 0$) at room temperature t_o is characterized by a slow increase in the yield strength σ_y, reaching values of 1.1–1.25 in about 30–40 years τ; furthermore, the ratio of the yield strengths $\sigma_y(\tau)$ to the tensile strengths decreases.

- Thermal aging (curves 2^I and 2^{II}) of steels in the initial state ($e = \sigma = 0$) at elevated temperatures t_1 and t_2 ($t_1 > t_0$; $t_2 > t_1$) leads to an accelerated growth of the yield point $\sigma_\text{т}(\tau, t)$ at the initial stages of exposure (up to 10^3–10^4 h) with its subsequent reduction (steel over ageing).

- Deformation aging (curve 3) of steels in the riveted state for $e > 0$ even at room temperature t_0 gives a smaller change of $\sigma_y(\tau, e)$ than the natural one.

- Dynamic aging (curve 4) at elevated temperatures in the plastically deformed state ($e > 0$) under stress conditions ($\sigma > 0$) can be accompanied at first by an insignificant increase, while later there is a fall in yield strength $\sigma_y(\tau, t, e, \sigma)$ and strength $\sigma_u(\tau, t, e, \sigma)$ with a decrease in the degree of hardening of tube steels in the plastic area.

In all cases of aging (curves 1–4), the ratio of the yield strengths σ_y to the tensile strengths σ_u increases (due to a smaller change in the tensile strength σ_u as compared to the yield point σ_y).

In the normative strength calculations [10], it is suggested not to take into account the areas of increase in the yield strength $\sigma_y(\tau, t, e, \sigma, N)$ due to aging, which goes to the margin of safety. In the refined basic and normative calculations of the strength of pipelines, one should take into account [4–9, 14–16]:
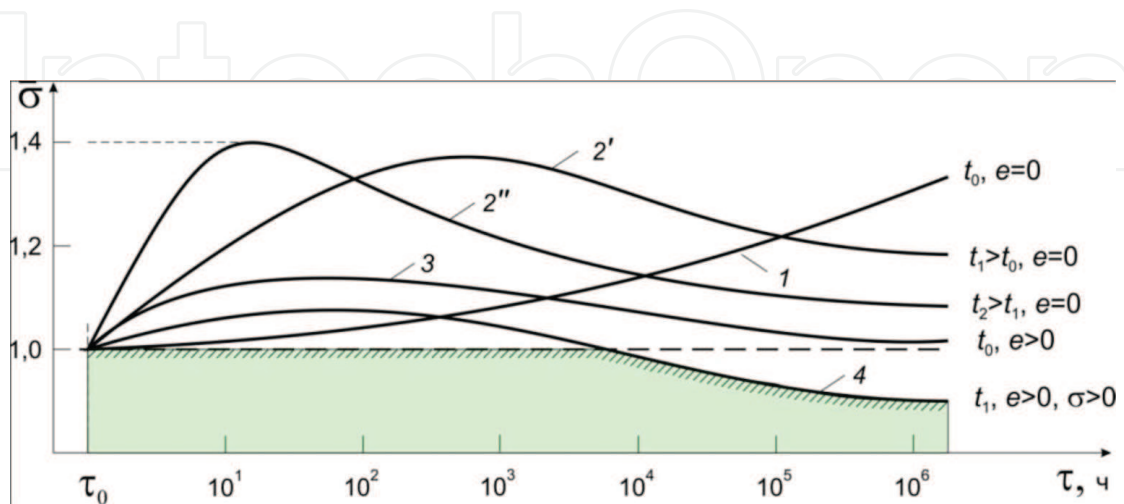

Figure 5. Scheme of aging processes of pipe steels.

- Continuous σ_u under all types of aging and degradation and the change in values σ_y and σ_u in Eq. (6)

- Effects of degradation of mechanical properties—decrease in relative yield point $\overline{\sigma}_y = \overline{\sigma}_y/\sigma_u$; $\overline{\sigma}_y(\tau, t, e, \sigma, N) \leq 1$;

- The decrease in plasticity (δ_κ from **Figure 2**), which accompanies aging and degradation, as well as the fracture toughness

In accordance with the above, based on Eqs. (2)–(5), and taking into account **Figures 2–5**

$$n_y = \frac{\sigma_y(\tau, t, \sigma, e, N)}{\sigma_{n\max}^s},$$ (7)

$$n_y/n_u = \sigma_y(\tau, t, \sigma, e, N)/\sigma_u(\tau, t, \sigma, e, N).$$ (8)

Equations (7) and (8) mean that the safety margins n_y and n_u are dependent on the aging and degradation processes of the tubular steels, time-dependent τ, temperature t, the cyclicity N, and the stress-strain state $\sigma - e$. This circumstance, which was not explicitly reflected in domestic [1, 2] and foreign [11, 12] regulatory materials, is to be taken into account in promising developments of pipe strength standards.

In [2–5], an experimental analysis was made of the time-dependent change in the characteristics of the mechanical properties of tube steels, primarily the yield strength σ_y and strength σ_y from the tensile tests of samples cut from the pipes in the initial state and after prolonged use. The time τ was varied from $\tau \cong 5 \times 10^{-2}$ to 3×10^5 h, operating temperature from -45 to $+50°C$, stress σ from $0.6 \sigma_y$ to $1.0 \sigma_y$, and deformation e from 0.8×10^{-3} to 3×10^{-3}.

The averaged data from these tests showed that the reduction of the yield strength $\sigma_y(\tau, t, e, \sigma, N)$ during exploitation from the initial τ_0 to the maximum of $\tau = 2, 3 \cdot 10^5$ h was 10–15% of the yield strength σ_y. Meanwhile, the ratio of the yield strengths to the tensile strengths increased by 1.15–1.2. This means that the margin n_y of the yield strength σ_y can be reduced by 1.1–1.17 times, and the margin n_u of the ultimate strength σ_u by 1.20–1.25 times. This corresponds to the generalized statistical experimental data from Transneft, obtained during tests of laboratory samples from actually operated pipes.

However, it should be borne in mind that the bulk of pipeline damage is associated with the most severe damage of surface layers of pipes (due to corrosion, erosion, mechanical impacts). In the standard tensile testing of samples (with surface layers removed during their manufacture), this type of damage has little effect on the strength characteristics σ_y and σ_u. For the experimental evaluation of the effect of surface damages, other tests are carried out. For example, cyclic bending tests of samples of full-scale gauge without surface treatment showed a reduction in the endurance limits at basic $N = 10^5 - 10^6$ by 15–18% [16]. This should affect the abovementioned decrease in margins n_τ and n_σ (up to 10–15%).

For these margins n_y and n_u, the degradation of pipelines is significant due to a decrease in time τ because of corrosion and erosion of the wall thickness δ that is included in Eq. (1) for

determining the nominal maximum operating stresses $\sigma^s_{n\max}$. As shown by laboratory tests and observations of the actual processes of metal loss while in the operation due to these mechanisms, the rate of corrosion and erosion reduction of the wall thickness $d\delta/d\tau$ can be from 0.05–0.1 to 0.3 mm/year. With wall thicknesses from 10 to 30 mm, the decrease of margins can reach 10–30%.

Thus, the aging of tubular steels and the degradation of pipes can, in the course of operation, with unfavorable combinations of all the abovementioned damaging factors lead to a substantial reduction in determined margins n_y and n_u and breach of strength as shown by Eqs. (1), (7), and (8). The number of such cases in real operation [3–5, 14] in the period of 1970–2015 gradually decreased from 1.2–1.0 to 0.12–0.14 damages per 1000 km per year.

6. Analysis of resistance to the development of cracks

A special place in the analysis of the pipeline strength is and will be occupied by the problems of their crack resistance and survivability, when formation and development of cracks of technological and operational origin are observed [3–6, 13–19]. In calculating the strength of pipelines with cracks of depth ℓ in thickness and length a over the surface, equations and criteria for linear and nonlinear fracture mechanics are used [3–7, 12, 13]. Then, the local stress-strain state at the crack tip is determined from the solution of the boundary value problem by numerical methods with defining of stresses $\sigma^s_{\max\kappa}$ and deformations $e^s_{\max\kappa}$:

$$\left\{\sigma^s_{\max k}, e^s_{\max k}\right\} = \sigma^s_{n\max} \cdot K_{\sigma\ell}, \tag{9}$$

where $\sigma^s_{n\max}$—maximum rated stress in Eq. (1); and $K_{\sigma\ell}$—effective coefficient of stress concentration in the zone of cracks.

The value $K_{\sigma\ell}$ is determined on samples with cracks:

$$K_{\sigma\ell} = F_\ell\{D, \sigma, \ell, a, S_*\}, \tag{10}$$

where $F_\ell\{D, \sigma, \ell, a, S_*\}$—function of pipe geometry (D, δ) and cracks (ℓ, a); and S_*—the structural parameter of the material, determined experimentally when testing samples with cracks.

Since $\sigma^s_{\max\kappa} > \sigma^s_{n\max}$ and $F_k\{D, \delta, \ell, a\} \geq 1$, then safety margins from Eq. (7) for pipes with cracks taking into account Eq. (9) will be further reduced (**Figure 6**):

$$\left\{(n_y)_\ell, (n_u)_\ell\right\} = \{n_y, n_u\}/F_k\{D, \delta, \ell, S_*, a\}. \tag{11}$$

In general, all the parameters of Eqs. (9)–(11) are deterministic, statistical, and probabilistic.

In calculating the strength of pipelines with defects, two basic estimated defect sizes are introduced:

- ℓ_o – Initial size (depth) of the defect, determined by the accepted methods of flaw detection (with their resolving power, sensitivity)
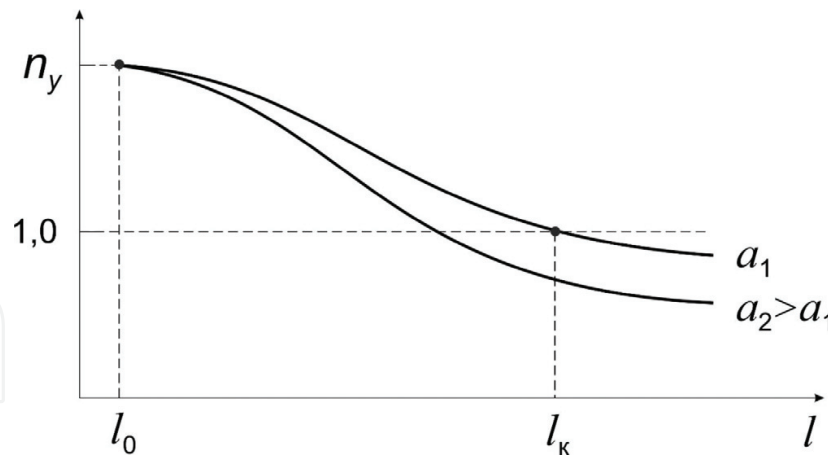
Figure 6. Influence of defects (such as cracks) on safety margins.

- ℓ_κ – The critical size (depth) of the defect at which the margin of safety n_y (or n_u) in Eq. (10) becomes less than 1

The calculations ℓ_κ take an elliptical ($\ell/a \approx 1/3$) or extended ($\ell/a \rightarrow \infty$) fracture shape. Typically, the most dangerous ones are surface cracks, taking into account more intensive accumulation of corrosion, erosion, and mechanical damage in the surface layers.

The second and most common way of assessing the strength of pipelines is to estimate margins $(n_y)_e$ and $(n_u)_e$ according to the equations and criteria of linear and nonlinear fracture mechanics [3, 7, 10, 16]. In this approach, the stress intensity factors are determined by the calculation for the given σ^s_{nmax} in Eq. (1) and $F_k\{D, \delta, \ell, a\}$ in Eq. (9):

$$K^s_I = \sigma^s_{nmax}\sqrt{\pi\ell} \cdot F_k\{D, \delta, \ell, a\} \tag{12}$$

When a sample or a pipe with a crack breaks up, a critical value of the stress intensity factor is reached at the crack tip in accordance with the linear fracture mechanics. Then, in calculating the crack, resistance (survivability) of pipes with cracks by analogy with Eq. (2) introduced a margin by the stress intensity factor:

$$n_k = \frac{K_{Ic}}{K^s_I}. \tag{13}$$

By the values of K^s_I and K_{Ic} and Eqs. (9) and (13), the equation below can be obtained:

$$\left\{(n_y)_\ell, (n_u)_\ell\right\} = \{n_y, n_u\} \cdot \frac{K_{Ic}}{\{\sigma_y, \sigma_u\}\sqrt{\pi\ell} \cdot F_k}. \tag{14}$$

The difference in margins according to Eqs. (11) and (14) should not be significant.

In the event of plastic deformations, instead of the stress intensity factors K_I and K_{Ic}, the strain intensity factors should be used [4, 6, 8].

A generalized analysis of the strength, resource, reliability, survivability, and safety of complex technical systems of pipeline transport is made in one of the volumes [17] of the multivolume series "Safety of Russia."

7. Statistical characteristics and probabilistic modeling of pipeline systems

Multiparameter pipelines with a wide range of service lives are functioning nowadays in Russia and in various countries across the world, according to parts 1 and 2 (**Figure 7**).

In further analysis of their initial and residual strength, durability, and crack resistance, both statistical data on service life τ and statistical data on changes in the mechanical properties of tubular steels σ_y, σ_u, K_{Ic}, as well as on developing defects ℓ, should be taken into account. This consideration can be performed on the basis of Eqs. (1)–(15) in both deterministic and statistical forms.

According to statistical data [20] on oil pipelines of Russia with a total length of more than 70,000 km (see **Table 1**), about 70% of them have a service life of more than 30 years. Their age structure is shown in **Figure 7**.

Statistical studies of mechanical properties (tensile strength σ_u) of 29 tube steels were carried out in 217 pipe sections manufactured at 14 plants. Upward bias from data on technical conditions was revealed in 8.9% cases and downward bias 2.6%.

Primary and repeated in-tube condition diagnostics on the length of more than 80,000 km of oil and gas pipelines revealed the presence of unacceptable corrosion and mechanical and erosive damage in 0.2–0.3% of pipes. This required repair and restoration works, as well as replacement of pipes or its sections. These works over the past 20 years have made it possible to reduce the frequency of accidents on pipelines from 0.14–0.16 to 0.09–0.10 per 1000 km per year.

The generally recognized statistical characteristic of the technical condition and safety of pipelines with due regard of their period of operation is [1, 3–7, 17–20] the number of system failures (failures $N^o(\tau)$) generated per time unit. The failure of a specific section of the pipeline is a very
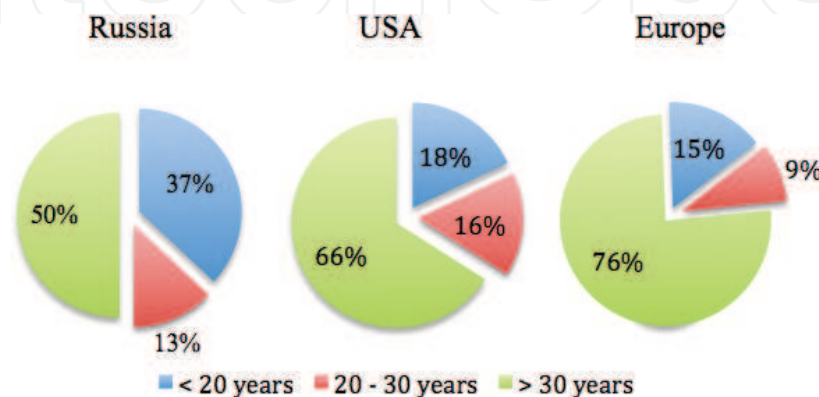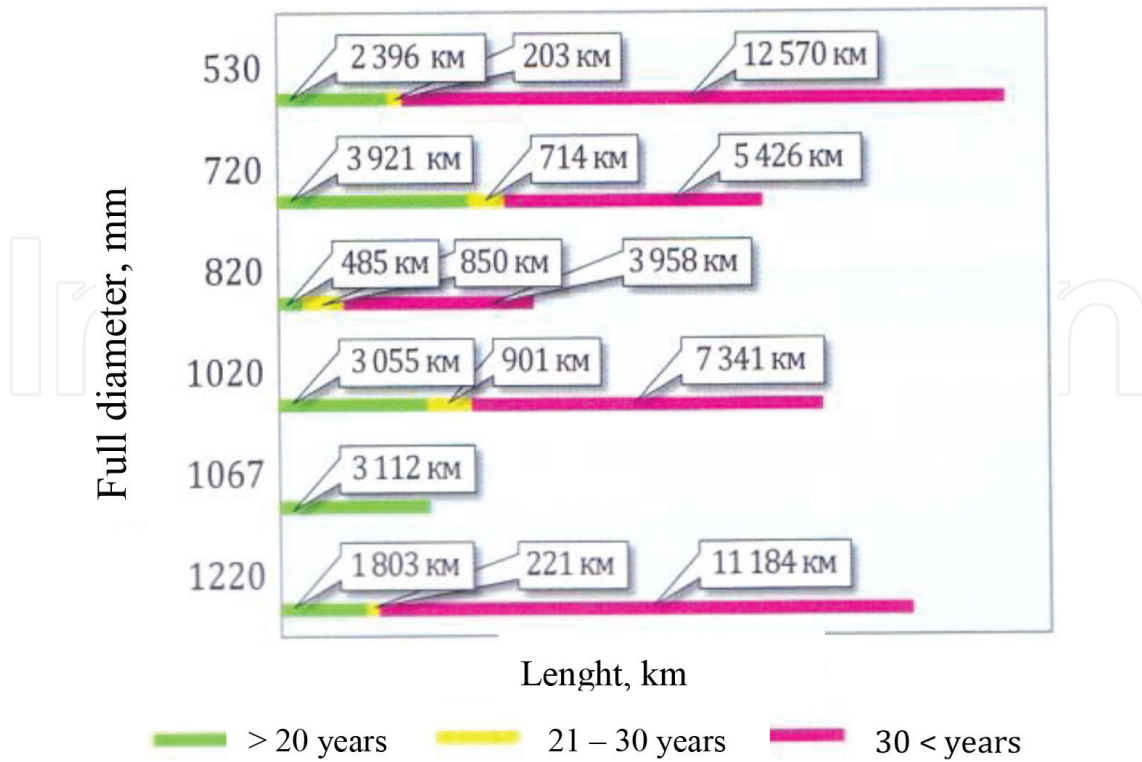

Figure 7. Statistics on the service life of pipelines.

Figure 8. Age structure of long-term running main pipelines of large diameter.

rare event, even for a fairly long period of time τ. But taking into account the considerable length of the whole system (more than 70,000 km), the reduced frequency or failure flow $P^o(\tau)$ at the length L (L = 1000 km) will have a finite value depending on the time of operation τ^s:

$$P^o(\tau) = \frac{dN^o(\tau)/d\tau^s}{L}. \tag{15}$$

The failure flow $P^o(\tau)$, in our country and abroad, of oil and gas pipelines decreases over time —from 0.3 to 0.4 in the 1960s and 1970s to 0.012–0.015 at the present.

According to Eq. (15), the reliability $P_o(\tau)$ of section L at a given time τ can be estimated [1, 4, 6, 7, 18] by the failure flow $P^o(\tau)$:

$$P_o(\tau) = 1 - P^o(\tau). \tag{16}$$

In this case, the value of $P_o(\tau)$ can be considered as a statistical and probabilistic indicator of the technical risk $R_o(\tau)$ of the failure:

$$R_o(\tau) = 1 - P^o(\tau) \tag{17}$$

On the basis of (16) and (17), the safety $S^o(\tau)$ of the MPS functioning at $\tau = \tau^s$ can be considered as.

$$S^o(\tau)=1-R_o(\tau)=P_o(\tau)$$ (18)

According to operational statistical data on failures N^o and failure flows $dN^\circ/d\tau$, the standard (permissible) operating time $[\tau]$ can be established—a resource of reliable operation excluding the transition of the MPS to the critical (ultimate) state.

Operational experience shows that the service life of the pipeline, as well as of other complex technical systems, can be conveniently divided into three main periods (**Figure 9**):

- Run-in period (τ_I), when there is a high failure rate (N^o), associated with unacceptable defects in construction and installation works and factory defects in pipes

- Stabilization period (τ_{II}), when the number of failures is minimal and their increase is insignificant

- Wear period (τ_{III}), associated with a steady increase in the number of failures and a decrease in throughput due to the occurrence of damage accumulation processes and the formation and development up to critical dimensions (K) of the initial and operational defects of metal pipes, welded joints, protective coatings, etc.

For mastered deterministic technologies of designing and manufacturing, the following correlations are fulfilled:

$$\tau_k = \tau_I + \tau_{II} + \tau_{III}.$$

$$\tau_I << \tau_{II} < \tau_{III}.$$ (19)

The allowed period $[\tau]$ of reliable operation of pipelines based on the allowed failure flow may include periods τ_I and τ_{II} and part of the τ_{III} period:
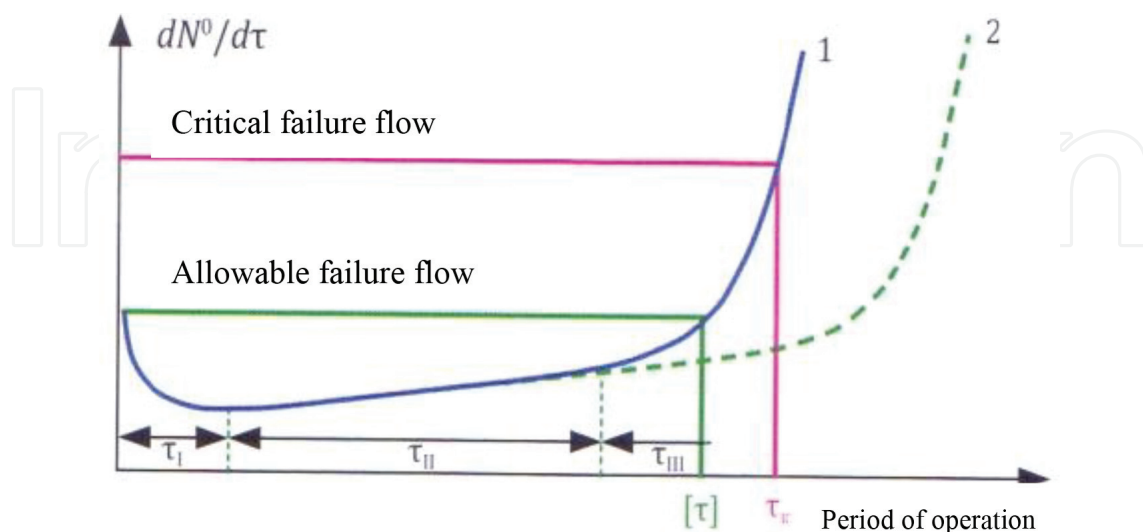

Figure 9. The failure of technical systems in dependence from the period of operation.

$$\tau^s \leq \tau_I + \tau_{II} + k\tau_{III} < \tau_k, [\tau] = \frac{\tau_k}{n_\tau} \tag{20}$$

where k—coefficient of using the pipeline with damages ($k < 1$); and n_τ—service life margin.

Equations (15) and (16) are valid both for MPS and for their individual elements when failures are associated with the development in the length of time of operational defects. At the same time, for the main pipeline transport, the period of operation and margins n_τ with deterministic, statistical, and probabilistic approaches should be taken into account under Eqs. (15)–(20).

The period of stable operation of the pipeline according to Eq. (20) can be increased by carrying out special organizational and technical measures, including the implementation of local or major repairs, diagnostic surveys, efficiency improvement of the corrosion protection system, etc. The most important aim of these measures is the extension of the safe operation period for the entire system (MPS) as well as for individual sections and pipes (the transition from curve 1 to curve 2 in accordance with **Figure 9**), subject to specified safety and reliability parameters.

Considering economic consequences $V_o(\tau)$, failures $N^o(\tau)$, risks $R^o(\tau)$, and costs for improving reliability and safety $Z(\tau)$ allows us to evaluate the economic effectiveness of integrated measures to improve the working capacity of MPS:

$$V_o(\tau) = V^o(\tau)\big[1 - k_p P^o(\tau)\big] = V^o(\tau)P^o(\tau), \tag{21}$$

where $V_o(\tau)$ and $V^o(\tau)$—designed throughput of the system with and without consideration for reliability; and kp—coefficient of influence of failures on the throughput.

Therefore, in accordance with Eqs. (1)–(4), the requirements for MPS operation efficiency are inextricably linked to the high requirements for ensuring reliability $P_o(\tau)$, safety $S_o(\tau)$, and risk management $R_o(\tau)$ in the process of its operation $\tau = \tau^s$, which determines the priority importance of economic, environmental, and industrial safety of transportation of oil, oil products, and gas. These issues are assigned to the scope of strategic planning at the federal, regional, and sectoral levels.

Statistical information on the quantities σ^s and σ_u, σ_y makes it possible to construct the probability density functions $f(\sigma^s)$ and $f(\sigma_u, \sigma_y)$ (**Figure 10**) describing the operational loads (nominal σ^s and strength characteristics) from Eq. (21).

The probability of fracture P_p as an extremely dangerous (critical) failure, accident, and catastrophe will be determined by the overlapping of the distribution density functions $f(\sigma^s)$ and $f(\sigma_u, \sigma_y)$. In general, all the parameters of Eq. (21) are time-dependent $\tau = \tau^s$.

Parameter $P_p(\tau)$ is taken into account when assigning the safety margins $\{n_u, n_y\}$, and Eq. (2) makes it possible to estimate the strength properties in accordance with the following equation:

$$P_{p^o}(\tau) = 1 - P_p(\tau). \tag{22}$$

In the calculations for the permissible stress under codes and rules for building [16], this approach is reflected in the separation from the total factor of margin n factors of homogeneity k_o, overload $k_{\text{п}}$, and operating conditions m:
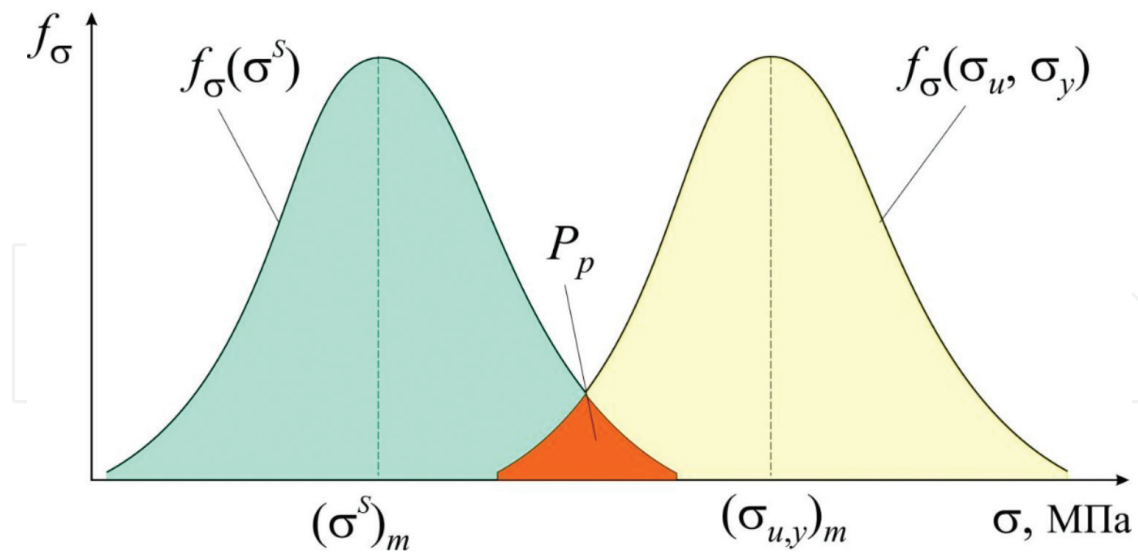
Figure 10. The scheme for determining the probability of fracture P_p by parameters of reliability and durability.

$$n = n(k_o, k_{\text{п}}, m) \tag{23}$$

As a result, the calculated strength $(\sigma_u^{\text{p}}, \sigma_y^{\text{p}})$ and load $\sigma_{\text{p}}^{\text{s}}$ are calculated by multiplying their mathematical expectation by the corresponding factors:

$$\sigma_{u,y}^{\text{p}} = k_o \left(\sigma_{u,\text{y}}\right)_m; \sigma_{\text{p}}^{\text{s}} = k_{\text{п}}(\sigma^s)_m. \tag{24}$$

The values of the factors in Eqs. (23) and (24) will depend on the assumed probability of fracture P_p, which is determined by the safety characteristic $S_o(\tau)$, the shape of the load distribution curves, and the strength in **Figure 9**:

$$k_o = 1 - z_p v_{u,\text{y}}; k_{\text{п}} = 1 + z_p v_s, \tag{25}$$

where $v_{u,\text{y}}, z_p$—factors of variability and quantiles of distribution of the strength characteristics of the material; and v_s—variation factor of the operational load.

Statistical analysis [5, 7] of the distribution functions of the mechanical properties of low-alloy steels (type 15ХСНД-С 0.12–0.18, Ci 0.4–0.7, Mn 0.4–0.7, Ni 0.3–0 (6%)) on a large number of n = 2500 laboratory samples from a 15-mm-thick sheet showed the acceptability of the use of the normal distribution law.

The generalization (**Figure 11**) of the test results of this steel at n = 22.000 samples with thickness of 5 to 24 mm revealed while increasing thickness δ, decrease of the yield strength for the probabilities P = (1%, 50%, 99%), as well as the variation coefficients v.

In the generally accepted normative calculations for the strength of the MPS, the time parameters τ are not explicitly introduced in Eqs. (1) and (2). They become necessary in the future specified calculations of the strength $\sigma_u(\tau)$ and $\sigma_y(\tau)$, reliability $P_o(\tau)$, safety $S^o(\tau)$, and efficiency $V_o(\tau)$ under Eqs. (15)–(25) in case of assessing the technical condition and extending the life of the functioning facilities and while designing new MPS:
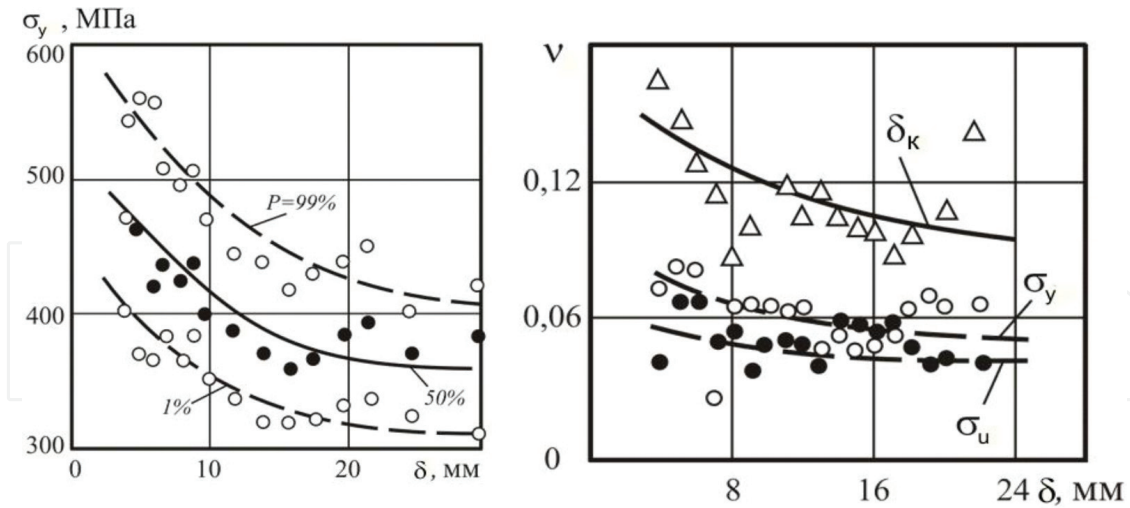
Figure 11. Dependence of yield strength σ_y, factors of variation v of yield strength σ_y, strength δ_u, and elongation δ_k from the rolled thickness δ.

The currently developed combined probability statistical method [4] makes it possible to assess the reliability $P_o(\tau)$ as a function of time τ^s on the basis of analysis of the initial deterministic, statistical, and probabilistic information about the design $K(\tau)$ and technological $T(\tau)$ features of MPS objects, the operating loads $Q(\tau)$ and environmental impacts $\Phi(\tau)$, stress-strain states in the coordinates $\sigma(\tau) - e(\tau)$ and probable mechanisms of accumulation of damage $d(\tau)$, and nucleation and development of defects $l(\tau)$.

The main design parameters will be determined under:

$$\{\sigma_u(\tau), \sigma_y(\tau), S^0(\tau), P_o(\tau)\} = \begin{cases} F_{\text{в}}\{K(\tau), T(\tau), Q(\tau), \Phi(\tau)\}; \\ F_p\{\sigma(\tau), e(\tau)\}; \\ F_n\{d(\tau), l(\tau)\}, \end{cases} \tag{26}$$

The abovementioned basic calculated dependencies in equations (1)–(26) allow [1, 3–7, 18–20] to make the transition from traditional deterministic engineering calculations of strength with the standard characteristics of mechanical properties σ_y, σ_u to calculations of strength, durability, crack resistance, reliability, and safety using new developing statistical and probabilistic methods of mathematical and physical modeling and refined calculations.

8. Conclusion

Ultimately, the problems of functional and strength reliability, resource, and safety of pipeline systems should cover all stages of the life cycle of facilities, representing three interrelated and interdependent processes: design, construction, and operation.

Designing while taking into account the prospects of statistical and probabilistic modeling of reliability and safety criteria should include the development and coordination of the technical

assignment with the introduction of basic requirements and criteria for strength, resource, and safety in accordance with applicable standards and development of physical and mathematical models for regular, damaged, and emergency situations. When designing facilities of new generations, strength analysis should be carried out in accordance to the basic standard and additional verification calculations, based on known internal and external influences and object characteristics, parameters of stress-strain state, and damaging factors with justification of initial resources for reliable and safe operation.

In the subsequent stages of design and manufacturing, reliability problems will be addressed, including selection, justification, and development of materials technology and control in accordance with existing norms and rules. Generally, for the manufactured elements of MPS, the actual mechanical properties and their deviations from the technical requirements, the level of real defectiveness, the geometry parameters, and their deviations should be established. On their grounds, the basic design parameters of strength and resource will be refined. At this stage, the issues of stability and safety of the elements require an analysis of possible failures for reasons of technological heredity.

At the operational stage, the system of routine diagnostics of the main characteristics of the MPS facility and the external environment that determine reliability will be specified, and information will be collected on confirming or adjusting design decisions on strength and resource. As the finalized design resource is exhausted, an evaluation of the residual life of safe operation should be carried out. To harmonize all deterministic, statistical, and probabilistic information for all stages of the life cycle of an object, it is necessary to use unified mathematical and physical models, calculation equations, criteria, and computer programs for MPS.

In the future, considering formation of a new legal and regulatory framework, in which the standardized requirements for safety $S^o(\tau)$, risks $R^o(\tau)$, as well as economic efficiency $V_o(\tau)$ will be of decisive importance, reverse solutions will be decided. At the same time, all the scientific and methodological potential accumulated in previous years will be fully utilized in selecting models, methods, design equations, and design parameters to achieve the required values $S^o(\tau)$, $R^o(\tau)$, and $V_o(\tau)$ in engineering design and technological and operational solutions for pipeline systems for oil and gas transportation.

Acknowledgements

Author details

Yuriy V. Lisin[1], Nikolay A. Makhutov[1], Vladimir A. Nadein[2]* and Dmitriy A. Neganov[1]

*Address all correspondence to: vladimir_nadein@ogsed.ru

1 The Pipeline Transport Institute (PTI, LLC), Moscow, Russia

2 LLC "Oil and Gas Safety – Energodiagnostika", Moscow, Russia

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