Chapter

Combined Calculated, Experimental and Determinated and Probable Justifications for Strength of Trunk Crude Oil Pipelines

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Abstract

Within the long-term Russian and foreign practice, deterministic methods of basic strength calculations have been developed and are being developed at the design stage of long-distance pipelines. Occurring operational damages, failures, accidents, and catastrophes show there are no direct substantiations for the prevention of such emergencies in the framework of existing calculations. In order to respond to these situations, the following are developed: additional precise deterministic, static, and probabilistic calculations with linear and nonlinear criteria of deformation and fracture mechanics, complex diagnostics of the state of the pipeline using in-line pigs, and laboratory, model, bench, and field tests of pipelines with technological and operational defects. The results of systematic scientific research and applied developments are presented.

Keywords: pipeline, strength, calculation

1. Statement of the problem

The trunk pipelines for transporting liquid and gaseous hydrocarbons are one of the main types of transport infrastructure in the world.

The most important pumped media are crude oil, gas, broad hydrocarbon fractions, and petroleum products. The total length of trunk pipelines in the world is more than 1.5 million km; in Russia it is about 230 thousand km, and the length of oil pipelines in the world is 170 thousand km; in Russia it is about 70 thousand km.

The length of the largest individual oil pipeline systems is Canada-USA 4700–5300 km with pipe diameters of 450–1220 mm, China-Kazakhstan 2200 km with a diameter of 813 mm, Azerbaijan-Georgia-Turkey 1768 km with a diameter of 1067 mm, Tanzania-Zambia 17,210 km with a diameter of 200–300 mm, and Italy-Germany 1000 km with a diameter of 660 mm.

In Russia, the largest oil pipelines are the Eastern Siberia-Pacific Ocean, 4740 km with a diameter of 1020–1200 mm, and Druzhba, 5500 km with a diameter of 520–1020 mm; eight trunk oil pipelines have a length of more than 1000 km.

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Figure 1.
Oil trunk pipelines (Russia).

The operating pressures in the main oil pipelines range from 2 to 10 MPa (**Figure 1**).

The trunk oil pipelines are operated in a very wide range of climatic conditions (from −70°C to +60°C) and natural hazards (seismic, landslides, geological faults), with ground, underground, and underwater laying.

Despite the large, more than century-old experience of research, testing, construction, and operation of oil trunk pipelines in the world and in Russia, there were large-scale accidents and disasters. These accidents were accompanied by the release of large amounts of oil (up to 100–600 thousand barrels) into the environment (land, water) with great environmental damage, fires, death and injury to people, and pollution of hundreds of hectares of land. Economic damages from such accidents are estimated at $ 10–100 million. The total number of accidents on oil pipelines in the world over the past 20 years is more than 2000, and the number of large oil leaks is more than 4500. For every million tons of pumped oil, 3–5 tons fall into leaks.

In general, the accident rate on the trunk oil pipelines is reduced. However, at present it is at the level of 0.1–0.3 per 1000 km per year (**Figure 2**).

These data indicate the need for further research and practical development to reduce accidents and improve the safety of trunk pipelines.

In recent years, four basic approaches to determining the strength, resource, and safety of oil pipelines have emerged:

- Deterministic
- Statistical
- Probabilistic
- Combined

2. Solving the problems of strength by basic and calibration methods

2.1 Basic deterministic calculations

The system of domestic and foreign trunk oil pipelines that took shape in the second half of the twentieth and the beginning of the twenty-first century is characterized by multistage creation and development of integrated approaches to justifying their strength [1–4]. These approaches were initially formed on the basis of the fundamental theories of thin-walled shells, classical theories of strength; they made it possible to form the main computational methods for the selection of computational schemes and computational cases and the assessment of static strength, taking into account the types of stress and limit states.

The basic strength condition was then recorded in the simplest form:

$$\sigma^{э}_{\max} \le \sigma_{on}, \tag{1}$$

where $\sigma^{э}_{\max}$ is maximum operating voltage stress and is hazardous stress.

For a thin-walled pipe with a diameter D with wall thickness ($\delta << D$), ring stresses are maximal:

(**Figure 3**).

$$\sigma^{э}_{\max} = \frac{P^{э}_{\max} \cdot D}{2\delta}, \tag{2}$$

where $P^{э}_{\max}$ is maximum operating pressure (**Figure 3**).

Figure 2.
Accidents on oil pipelines (Venezuela, China, Russia).

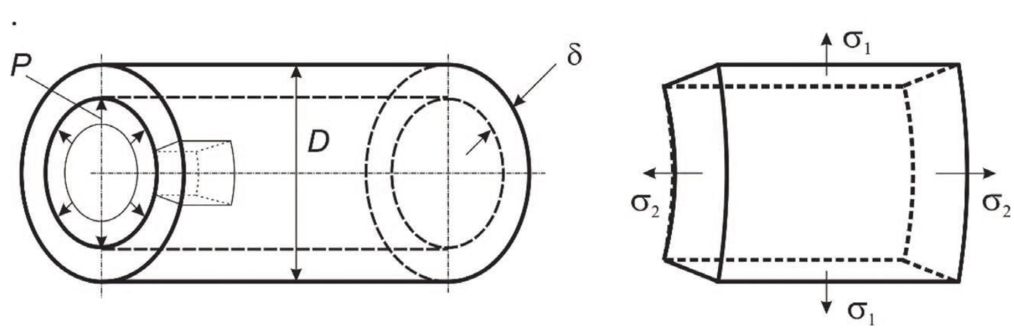

Figure 3.
The main design scheme.

Since in engineering calculations of static strength according to (1) and (2), a whole set of design, technological, and operational methods remained unclear, permissible stresses $[\sigma]$ with corresponding safety margins were entered into the calculation:

$$[\sigma] = \frac{\sigma_{on}}{n_{в}} = \min\left\{\frac{\sigma_{т}}{n_{т}}, \frac{\sigma_{в}}{n_{в}}\right\}. \tag{3}$$

Dangerous stresses were applicable ones corresponding to:

- Ultimate strength $\sigma_{в}$, which excluded the occurrence of fracture (the first significant limiting state).

- Yield strength $\sigma_{т}$ (or conditional yield strength $\sigma_{0,2}$), which excluded the formation of unacceptable plastic deformations (the second most significant limiting state). For modern pipeline systems transporting petroleum and petroleum products, a number of main life cycle stages, as measured up to 30–60 years, are introduced into the strength analysis:

- Feasibility study of the project

- Outline and detailed design

- Construction and testing of pipeline systems

- Operation of pipeline systems with diagnostic and repair and rehabilitation works

- The withdrawal of sections of pipelines or pipeline systems from operation

- For each of these stages and for the entire life cycle, to date, in our country and abroad, certain approaches and methods to substantiate strength have been formed.

These methods are divided into two main groups:

- Basic strength calculations

- Verification calculations of strength for the used construction material

The formation of methods of basic and calibration calculations is currently associated with the stages of the life cycle. At the same time, an important role is always played by scientific studies to substantiate the strength criteria, the choice of design schemes and design cases, followed by the introduction of safety margins. This is a scientific basis for solving applied problems of strength—the development of strength standards with their design characteristics (**Figure 4**).

For all pipe steels $\sigma_{т} \leq \sigma_{в}$ and to fulfill condition (3), the margins must satisfy.

$$1 \leq n_{т} \leq n_{в}. \tag{4}$$

The development of pipeline transport during the decades of the twentieth to twenty-first centuries [5, 6] was accompanied by a gradual increase in the

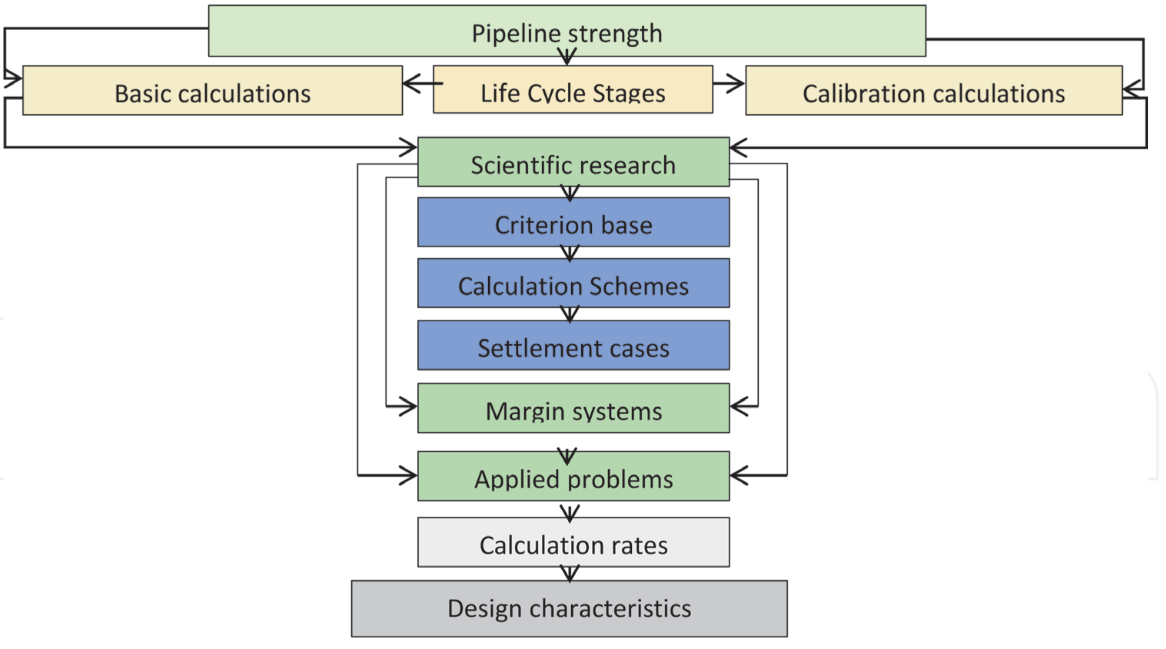

Figure 4.
Generalized scheme of research and rating of strength.

mechanical properties $\sigma_т, \sigma_в$ of pipe steels ($200 \le \sigma_т \le 800$, $350 \le \sigma_в \le 950$) and a decrease in strength margins ($2.8 \ge n_т \ge 1.5$, $4.0 \ge n_в \ge 1.8$).

Expressions (1)–(4) were and remain central to foreign strength standards [2–4]. In Russian practice [1, 4, 5], expressions (1) and (2) were retained, but the strength margins n_σ in (3) were presented in a differentiated form:

$$n_\sigma = \{n_т, n_в\} = \frac{n \cdot K_1 \cdot K_н}{m}, \tag{5}$$

where n, K_1, and $K_н$ are the reliability factors for load, material, and purpose ($n, K_1, K_н \ge 1$) and m is the operating condition ratio ($m \le 1$).

In view of **Figure 4** and expressions (1)–(5) in the feasibility study of the project, two main parameters are defined and assigned, $p^э_{max}$ and D, ensuring the specified pipeline performance.

At the stage of preliminary and detailed design, the main calculation is reduced to the calculated determination of the minimum wall thickness of the pipeline according to the given $p^э_{max}$ and D, taking into account economically and technologically reasonable choice of pipe steel with characteristics $\sigma_т, \sigma_в$ (according to technical conditions or standards):

$$\delta_{min} \ge \frac{p^э_{max} \cdot D}{2[\sigma]}. \tag{6}$$

Since the values $p^э_{max}$ at each of the calculated sections of the pipeline depend on their height position, which determines the hydrostatic part of the pressure, the calculated values δ_{min} are variable in length.

At the stage of construction and pre-hydraulic pressure tests $p^г \ge p^э_{max}$, calibration calculations with an assessment of the maximum hydraulic tests are carried out in accordance with (2), their comparison with permissible values in accordance with (3) and (5) and confirmation of the absence of destruction or the formation of unacceptable plastic deformations

$$\sigma^г_{max} = \frac{p^г \cdot D}{2\delta_{min}} \le \frac{\sigma_{on}}{n^г_\sigma}. \tag{7}$$

At the stage of operation for the time τ there is a possibility of accumulation of damage, and a decrease in wall thickness $\delta_{\min}(\tau)$ due to corrosion, erosion, as well as a change in mechanical properties $\sigma_{т}(\tau), \sigma_{в}(\tau)$.

These parameters are determined according to periodic in-line inspection, as well as according to mechanical testing of samples from damaged sections of pipelines. The verification calculation of the strength for this stage is reduced to the assessment of the strength margin $n_{\sigma}(\tau)$.

$$n_{\sigma}(\tau)=\frac{\sigma_{on}(\tau)}{\sigma^{э}(\tau)}; \tag{8}$$

$$\sigma_{э}(\tau)=\frac{p^{э}_{\max}\cdot D}{\delta_{\min}(\tau)}; \tag{9}$$

$$\sigma_{on}(\tau)=\{\sigma_{т}(\tau), \sigma_{в}(\tau)\}. \tag{10}$$

If for the analyzed stage τ margin по (8) is not less than in in (3) and (5), then the operation of the pipeline can be continued.

To calculate the estimated time τ_p of the next in-line inspection, it is necessary to have data on monitoring $\sigma_{т}(\tau_p), \sigma_{в}(\tau_p)$ and $\delta_{\min}(\tau_p)$ on the basis of previous in-line inspections operations.

If such initial information is absent, then the construction of calculated curves is possible:

$$\{\sigma_{т}(\tau), \sigma_{в}(\tau)\}=F\{(\sigma_{т}, \sigma_{в})\cdot\tau^{m_{\tau}}\}, \tag{11}$$

where m_{τ}—If such initial information is absent, then the construction of calculated curves is possible [6, 7] ($0\le m_{\tau}\le 0.03$ for τ in hours).

2.2 Statistical strength analysis

In actual practice, in the manufacture and testing of pipes, the construction of pipeline sections and the operation of pipeline systems, all specified parameters of expressions (1)–(11), are statistically variable, despite the determination of the main calculations in the design of pipelines throughout the system of design expressions.

The statistical analysis of the calculated parameters in the framework of the basic calculations of the strength of pipelines is aimed at establishing:

- Minimum (min), average (m), and maximum (max) parameter values
- Comparability with the values adopted in the project documentation
- Deviations of the calculated parameters to the dangerous and safe side in comparison with the statistically determined.

On this basis, two decisions are made about the possibility or impossibility of further operations of pipelines.

In the first case, the main requirement for the strength of pipelines must be met; in the second case, the strength is considered not ensured if the maximum operating stresses exceed the allowable.

$$\sigma^{э}_{\max\ c} \le [\sigma]; \sigma^{э}_{\max\ c} > [\sigma]. \tag{12}$$

For the scientific substantiation of the need and possibility of extending the operation of pipelines in cases of failure to meet the strength conditions, it is possible to reduce the operating pressure to level.

$$p^{э}_{c} < p^{э}, \quad \text{when } \sigma^{э}_{c} < \sigma^{э} \le [\sigma] \tag{13}$$

Simultaneous fulfillment of conditions (1)–(3) requires the mandatory calculation of the strength of the pipeline—its pipes and sections, where the realization of expression (12) is detected.

This calculation should include:

- Maximum values of operating pressure $p^{э}_{\max}$
- Maximum values of the diameter $D_{\max}$ of the pipe or section of the pipeline
- Minimum wall thickness $\delta_{\min}$
- The minimum values of the characteristics of mechanical properties $\sigma_{\text{T}\min}, \sigma_{\text{B}\min}$.

In this case, you can write

$$\sigma^{э}_{c} = F_{\sigma}\left\{p^{э}_{\max}, D_{\max}, \delta_{\min}\right\} \le [\sigma] = \min\left\{\frac{\sigma_{\text{B}\min}}{n_{\text{B}}}, \frac{\sigma_{\text{T}\min}}{n_{\text{T}}}\right\} \tag{14}$$

The strength condition according to expression (14) should be checked according to the statistical analysis and when conditions (12) are fulfilled.

At the same time, both for condition (12) and for conditions (13) and (14), it is advisable to give an assessment of the strength according to (1):

- With average values of all parameters $p^{э}_{m}$, D_m, δ_m, and $\sigma_{\text{T}\ m}, \sigma_{\text{B}\ m}$

$$\sigma^{э}_{c} = F_{\sigma}\left\{p^{э}_{m}, D_m, \delta_m\right\} \le [\sigma] = \min\left\{\frac{\sigma_{\text{B}\ m}}{n_{\text{B}}}, \frac{\sigma_{\text{T}\ m}}{n_{\text{T}}}\right\} \tag{15}$$

- At extreme (extreme) values $p^{э}_{\max}$, $\delta_{\max}$, $D_{\min}$, and $\sigma_{\text{T}\max}, \sigma_{\text{B}\max}$

$$\sigma^{э}_{\max} = F_{\sigma}\left\{p^{э}_{\max}, D_{\min}, \delta_{\max}\right\} \le [\sigma] = \min\left\{\frac{\sigma_{\text{B}\max}}{n_{\text{B}}}, \frac{\sigma_{\text{T}\max}}{n_{\text{T}}}\right\}. \tag{16}$$

Thus, according to (12)–(16), the calculated (average, minimum, maximum) values of $p^{э}$, D, δ, and $\sigma_{\text{T}}, \sigma_{\text{B}}$ are due to a whole range of design, technological, and operational factors.

2.2.1 Operating pressure

The statistical nature of operating pressures $p^{э}$ satisfies inequalities.

$$p^{э}_{\min} \le p^{э}_{m} \le p^{э}_{\max} \tag{17}$$

due to changes in the actual pressures in a given pipe or in a given section of the pipeline due to

- Actuation systems to maintain the specified working pressure at pumping stations

$$p^{э}_{н\ \min} \le p^{э}_{н\ m} \le p^{э}_{н\ \max} \tag{18}$$

- Deterministic design and actual operational differences of hydrostatic pressures $\Delta p_{г}$ from changes in the profile of the heights of laying pipelines

$$\Delta p^{э}_{г\ \min} \le \Delta p^{э}_{г\ m} \le \Delta p^{э}_{г\ \max} \tag{19}$$

- Deterministic design pressure changes $\Delta p_{гс}$
- Deterministic design pressure changes due to changes in hydraulic resistance to the movement of oil and oil products (due to changes in flow areas, viscosity, and temperature of the transported working fluid)

$$\Delta p_{гс\ \min} \le \Delta p_{гс\ m} \le \Delta p_{гс\ \max} \tag{20}$$

- Deterministic design and actual operating pressure changes due to external effects on the pipeline (seismic, temperature, vibration, aero-hydrodynamic)

$$\Delta p_{в\ \min} \le \Delta p_{в\ m} \le \Delta p_{в\ \max} \tag{21}$$

In the basic calculations using expressions (1)–(11), for deterministic and statistical estimates of the static strength of pipelines, pressure components should be included when the pipelines are operating at maximum design conditions:

$$p^{э}_{р} = p^{э} + \sum \Delta p^{э}. \tag{22}$$

Deeper in scope, cyclic pressure changes due to software changes in pipeline operation modes (start-up, shutdowns, performance change—throughput) are subject to accounting for cyclic strength and durability calibration calculations. Statistical information on the change in pressure is obtained from the registration data at pumping stations.

2.2.2 Diameter of pipelines in operation

The diameter D, which is included in expressions (1), (4)–(6), and the pipeline, is characterized by the scattering of its actual values. It is due to pipe manufacturing technology and is reflected in the maximum and minimum technological tolerances on the diameter $\Delta D_{т}$:

$$\left\{D^{т}_{\max}, D^{т}_{\min}\right\} = D_{п} \pm \Delta D_{т}, \tag{23}$$

where $D_{п}$ is design diameter.

Values $\Delta D_{т}$ in either direction may be the same or different.

The diameters of $D^{э}$ pipes in various parts of pipelines that are fixed during operation during inspections and diagnostics of pipelines may differ from the diameters $D_{т}$ after the manufacture of pipes:

$$\left\{D^{э}_{\max}, D^{э}_{\min}\right\} = \left\{D^{т}_{\max}, D^{т}_{\min}\right\} \pm \Delta D^{э}. \tag{24}$$

Values $\Delta D^{э}$, as a rule, have a positive value due to the possible deformation under the action of test or operating modes with increased pressure.

The second factor of change in diameters $D^{э}$ can be ovalization of the cross-section during transportation, construction, and operation (usually while maintaining the length of the perimeter of the pipeline):

$$D^{э} = F_D\{D^{э}_{\min}, D^{э}_{\max}\}, \tag{25}$$

where $D^{э}_{\min}, D^{э}_{\min}$ are minimum and maximum diameter in the zone of ovalization.

For ovalized sections, the calculated determination of stresses according to (1) should take into account their increase.

The calculated justification of static strength in the framework of the basic calculations according to (1)–(21) should be mainly oriented:

- To the maximum values in $D_{\max}$ in (23) and (25)
- At maximum operating stress $\sigma^{э}_{\max}$

2.2.3 Pipeline wall thickness in operation

Pipeline wall thickness δ has the most significant effect on operating stresses $\sigma^{э}$ and strength conditions.

The statistical variation of values, as well as diameters D, is due to:

- Rolling sheet technology, which is a blank for pipes:

$$\{\delta^{т}_{\min}, \delta^{т}_{\max}\} = \delta_{п} \pm \Delta\delta_{т}, \tag{26}$$

where $\delta_{п}$ is design wall thickness and $\Delta\delta_{т}$ is technological tolerance for thickness.

The change in wall thickness during pipe rolling can be neglected, taking into account the main bending deformations.

When testing pipes at the manufacturing stage and during construction, it is possible to change the wall thickness downwards:

- Due to plastic deformations from high-pressure tests $p_{и}$

$$\Delta\delta_{и} = F_{\delta}\{p_{и}, \Delta D^{э}, \mu\}, \tag{27}$$

where μ is Poisson's ratio ($0.3 \le \mu \le 0.5$) and $\Delta D^{э}$ is a possible increase in the diameter $D^{э}$ of the pipeline, defined by (25).

- Due to corrosion and erosion damage

$$\Delta\delta_{кэ} = F_{\delta}\{p^{э}, \tau^{э}, c_{кэ}\}, \tag{28}$$

where $\tau^{э}$ is operation time and $c_{кэ}$ is the rate of corrosion erosion damage.

In the basic calculations of static strength according to the basic calculations of static strength according to the expressions (1)–(28), the minimum value of the wall thickness should be used:

$$\delta^{э}_{\min} = \delta_{п} - \Delta\delta_{т} - \Delta\delta_{и} - \Delta\delta_{кэ}. \tag{29}$$

Expression (29) under condition (14) will mean the maximum increase in operating stresses $\sigma^{э}$.

2.2.4 Characteristics of mechanical properties

Mechanical properties with strength characteristics $(\sigma_{в}, \sigma_{т})$, (R_1, R_2), as well as $p^{э}, D, \delta$ are stochastic. In order to ensure and justify the static strength of pipelines ,their minimum values should be entered into the calculation. The statistical variation in the characteristics of the mechanical properties of pipe steels is determined by a set of technological factors:

- Chemical composition and structural structure (grain size d)
- Modes of thermal and thermomechanical $(t_{т})$ processing
- The level of preliminary plastic deformations e_n during sheet rolling, rolling of tube blanks, and testing of pipes, sections, and sections of pipelines
- Temporary factors of aging and degradation in time τ

$$\left\{\sigma_{в}^{э}, \sigma_{т}^{э}\right\} = F_{\sigma}\{d_3, t_{п}, e_n, t^{э}\}. \tag{30}$$

For widely used pipe steels, the increase in strength characteristics $\sigma_{т}, \sigma_{в}$ is usually combined with a decrease in ductility.

In the main calculations of the strength of pipelines, it is recommended to use statistical data on the reduction of strength characteristics:

$$\left\{\sigma_{в}^{э}, \sigma_{т}^{э}\right\} = \min\{\sigma_{в}, \sigma_{т}\}. \tag{31}$$

2.2.5 Reflection of statistical factors of strength in margin

Use in domestic and foreign basic regulatory calculations of the strength of the system of strength margins n_{σ} (when calculating the permissible stresses $[\sigma]$) and reliability coefficients K_1, K_2, m, and n (when calculating the limiting states and resistances) makes it possible to obtain a connection between them in the form of expression (5).

All coefficients of expression (5) in a deterministic form, taking into account the statistics of design parameters for expressions (12)–(31), reflect the general variation of design, technological, and operational strength factors.

The strength margins n_{σ} of (5) in the deterministic basic and calibration statistical calculations take into account the level of the necessary reduction of operating stress $\sigma^{э}$ compared to dangerous stresses $\left(\sigma_{\max}^{э} < \sigma_{оп}\right)$:

$$n_{\sigma} = \frac{\sigma_{оп}}{\sigma_{\max}^{э}}. \tag{32}$$

At the same time, dangerous stresses $\sigma_{оп}$ are understood not only as deterministic but also as statistical limits of strength $\sigma_{в}$ (to exclude one-time static damage) and plasticity $\sigma_{т}$ (to exclude one-time static damage) and plasticity (to prevent the formation of unacceptable plastic deformations):

$$\sigma_{оп} = \min\{\sigma_{в}, \sigma_{т}\}. \tag{33}$$

The statistical information about the values $\sigma^{э}$ is obtained on the basis of the analysis of the stress–strain state by statistical parameters $p^{э}, D, \delta$ on the basis of the entire system of expressions (1)–(33).

In combination with the statistical data on the hazard values of the criterial characteristics $\sigma_{оп}$ in the form of tensile strengths $\sigma_{в}$ and yield strengths $\sigma_{т}$ (or design resistances R_1, R_2), a scatter can be obtained $n_{\sigma}(n_{в}, n_{т})$:

$$n_{\sigma\min} = \left\{ \frac{\sigma_{\text{В min}}}{\sigma^{э}_{\max}}, \frac{\sigma_{\text{Т min}}}{\sigma^{э}_{\max}} \right\}; n_{\sigma \max} = \left\{ \frac{\sigma_{\text{В max}}}{\sigma^{э}_{\min}}, \frac{\sigma_{\text{Т max}}}{\sigma^{э}_{\min}} \right\}. \tag{34}$$

To make decisions about the admissibility of safety margins, n_{σ} should be estimated, and their average values

$$n_{\sigma \text{ cp}} = \left\{ \frac{\sigma_{\text{В } m}}{\sigma^{э}_{m}}, \frac{\sigma_{\text{Т } m}}{\sigma^{э}_{m}} \right\}. \tag{35}$$

The strength of the pipeline, determined by the allowable stresses in the statistical interpretation, can be considered as secured if the normatively specified margin $n_{\sigma н}(n_{вн}, n_{тн})$ satisfies the inequality

$$n_{\sigma \max} \geq n_{\sigma m} \geq n_{\sigma \min} \geq n_{\sigma \text{Н}}. \tag{36}$$

According to these statistics, it is possible to quantify statistical variations of the coefficients m, n, K_1, and $K_{н}$. On this basis, you can make a conclusion about the strength of the pipeline, if combinations are performed:

$$\{m_{\min}, K_{\text{IImax}}, K_{\text{н max}}, n_{\min}\} > \{m, K_1, K_{н}, n\}_{н}. \tag{37}$$

Failure to comply with conditions (36) and (37) requires making decisions about conducting refined basic and calibration calculations by deterministic and statistical methods.

2.3 Basics of probabilistic strength calculations

The accumulation of statistical information in the form of histograms of the main design parameters of strength makes it possible to proceed to a probabilistic analysis in the form of a distribution of strength. They are reflected in regulatory calculations for limiting states and limiting resistances [5] through the safety factors for the material, load, working conditions and purpose, and load in expression (25):

The essence of this analysis [1, 6, 8] is:

- to obtain the probability density functions p of external and internal effects (the number of pressure $p^{э}$) and the corresponding design stresses $\sigma^{э}$ and design resistances (yield strength σ_T and strength $\sigma_{в}$) with the subsequent determination of the probability of failure P_p in areas, where areas with extremely low probabilities ($P_p \leq 10^{-7}$);

- to construct probability functions $P(\sigma^{э})$ and $P\{\sigma_T, \sigma_{в}\}$ with the definition of the relationship between strength margins $\{n_T, n_{в}\}$ and given probabilities $P(\sigma^{э})$, $P\{\sigma_T, \sigma_{в}\}$, corresponding to the volume of the initial statistical and probabilistic information.

There is a simple relationship between probability P and the amount of initial statistical information:

$$n = \frac{i - 0,5}{P}, \tag{38}$$

where i is the sequence number of the measured value and n is the total number of measurements.

With a commonly used sample of 20 measurements, the value is $P = 2.5{\cdot}10^{-2}$ (or 2.5%).

To estimate the values of P at the level of 10^{-2} (or 1%) it is necessary to make already 50 measurements, and for the probability of 10^{-4} – 5000.

In statistical and probabilistic studies of the mechanical properties of structural steels, the volume of samples n is in the range of 20–22.000 [6, 10]. According to the histogram of the limit distribution functions $\sigma_{т}, \sigma_{в}$, the functional F is obtained for the strength margins $n_{т}, n_{в}$:

$$\{n_T, n_в\} = F\{P(\sigma^э), P(\sigma_T, \sigma_в)\} \tag{39}$$

The number of laboratory samples of steel 17G1S, cut from pipes in the initial state and after 40 years of operation is 28.

To solve probabilistic problems of strength in terms of expression (39) in the zone of small probabilities of destruction P_p, a large amount of statistical information is needed with samples measured in the hundreds and thousands, which is practically impossible in many real cases. In this connection, it is more promising to use expressions (38) and (39), which allow $\{n_T, n_в\}$ estimating reserves for a given probability P of calculated characteristics, corresponding to the availability of experiments on the distribution functions, $P(\sigma^э)$ and $P\{\sigma_T, \sigma_в\}$, with the choices of tens and hundreds.

Figure 5 shows the scheme for the implementation of a probabilistic analysis of reserves: along the ordinate axis, the probabilities $P(\sigma^э)$ and $P(\sigma_в)$ on a scale corresponding to the normal distribution law. Then by the median values $\sigma^э_m$ и $\sigma_{вm}$ for the probability P = 50% and for other values of P (P < 50%).

$$(n_{\sigma в})_m = \frac{(\sigma_в)_m}{(\sigma^э)_m}; (n_{\sigma в})_p = \frac{(\sigma_в)_p}{(\sigma^э)_p}. \tag{40}$$

If, according to the results of statistical processing of values $\sigma^э$ and $\sigma_в$ the parameters of their probability distributions are obtained—(the coefficients of variation $V\sigma^э$ and $V\sigma_в$ and their average values $\left(\sigma^э_m\right)_m$and $(\sigma_в)_m$, then the calculated values $(\sigma_в)_p$ and $(\sigma^э)_p$ for a given probability P are obtained from the expressions.

$$\left\{(\sigma^э)p, (\sigma_в)_p\right\} = \{(\sigma^э)_m, (\sigma_в)_m\}\left(1 - Z_p\{V\sigma^э, V\sigma_в\}\right), \tag{41}$$

where Z_p is distribution quantile depending on P.

For coefficients of variation in the range of $V\sigma^э$ и $V\sigma_в$ in the range of 0.03–0.1 the calculated probabilities P_p are obtained when the margin factors $n_{\sigma в}$>1, 8 are in the range of 10^{-15} to 10^{-5}.

With the currently existing banks of data on operational load $\sigma^э$ and mechanical properties of pipe steels $(\sigma_{в}, \sigma_{T})$, it is more reasonable to consider not determining the values of P_p in the area of their low values, but determining the strength margins from (40) using the specified probability parameters P in the range of 10^{-4} to 10^{-5} and above.

On the basis of (5) and (41), it is possible to analyze changes in the regulatory strength margin $n_в$ taking into account the probabilistic characteristics of the operational loading $\sigma^э$ and the limits of strength $\sigma_В$:

$$n_p = n_в \frac{1 - Z_p \cdot V\sigma_в}{1 + Z_p \cdot V\sigma^э} = n_в \cdot \overline{n}_p, \tag{42}$$

where n_p is margin of strength for a given probability P and $\overline{n}_p$ is margin reduction ration$_в$. The relationship between $\overline{n}_p$ and P in (42) with $V\sigma_В = 0,05$ and $V\sigma^э = 0,08$ is shown in **Figure 6**. From the data in **Figures 5** and **6**, it can be seen that the greatest influence on the allowable change in the strength margins $n_в$ is observed when P decreases from 0.5 to 10^{-3}. Refinement of probabilistic calculations of strength at lower P does not make much practical sense.

The probabilistic approach acquires its practical relevance in the critical sections of trunk pipelines:

- At their intersections with other transport systems (rail, high-voltage, pipeline), with non-compliance with the allowable distances from other facilities and infrastructures
- On water transitions
- In zones of geological faults, landslides, and seismic effects

This approach becomes significant and necessary for those cases when the assigned service lives and estimated durability are developed, and the in-line inspections show increased defectiveness.

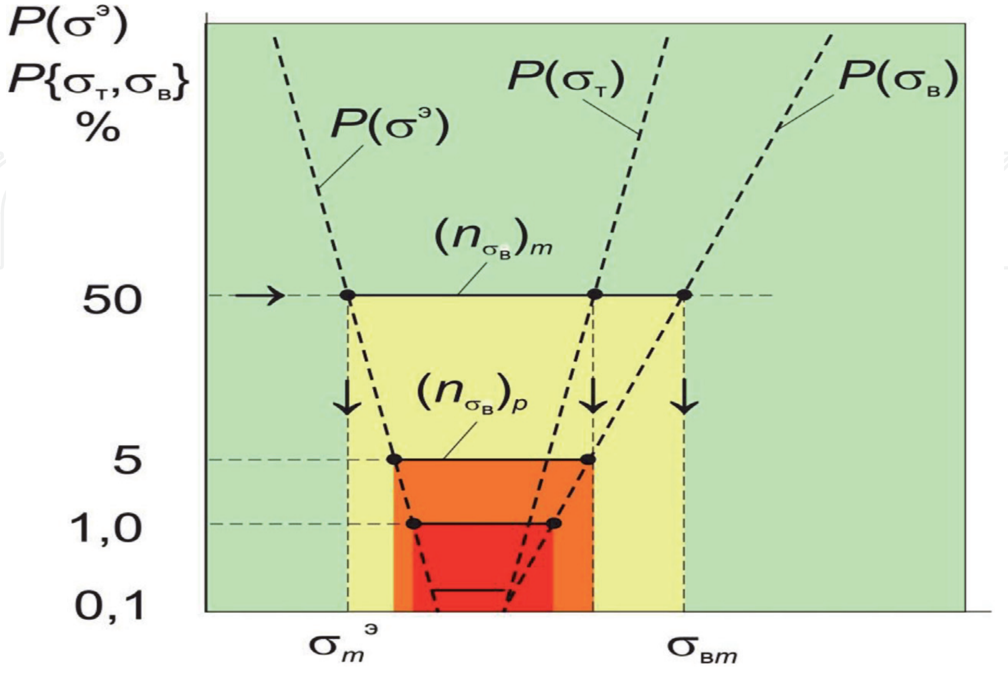

Figure 5.
Scheme for assessing the impact of probability P on the strength margin.

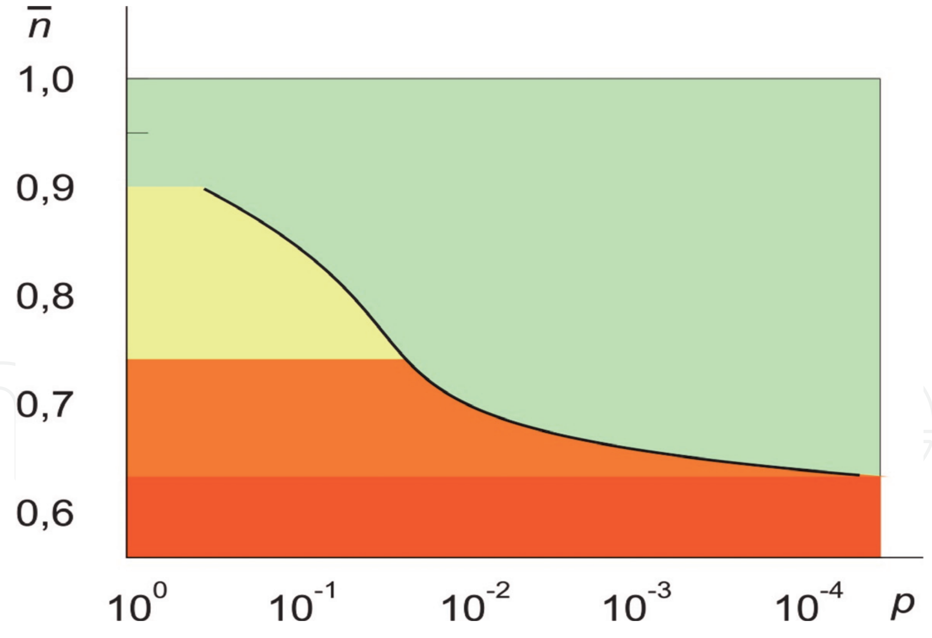

Figure 6.
Relative decrease in strength margins $\bar{n}$ with changing probabilistic characteristics of loading and mechanical properties.

3. Implementation of combined methods to substantiate strength

3.1 Formation of the structure of the combined methods

The generalized structure of the standard basic and calibration determination of the strength parameters of main oil pipeline systems discussed above (Section 2) reflects the theory and practice of computational and experimental substantiation of strength developed in our country and abroad for six to seven decades. The focus is on the trunk pipelines for the transportation of oil and oil products. The calculation of strength analysis is based on two methods—the method of calculation for permissible stresses (adopted in foreign practice) and the method of calculation for limiting states and limit resistances (adopted in Russian practice).

The most developed and applied is the deterministic strength calculation at the design stage. This solves the direct main problems of determining the wall thickness of the pipeline for given pressures, throughput of pipes and selected pipe steels. The same method is used at the stage of calibration calculations of the strength of the pipelines under construction and the majority of the pipelines being operated.

In those cases when it is necessary to calculate the substantiation of the strength of functioning pipelines with deviations from the design decisions and when defects in pipes occur outside the established norms, it is necessary to carry out calibration calculations using actual statistical information on all the calculated parameters. One of the tasks solved at the same time is the appointment of all the main design parameters according to the obtained statistical information. In these cases the preservation of regulatory reserves is typical.

For the most critical sections of pipelines, statistical strength analysis may be insufficient and unacceptable. Then probabilistic estimates of strength are required using the functions of the distribution of operational loading and the mechanical properties of pipe steels by the parameter of operation time. For these situations, it becomes possible to change the safety margins for the required probabilities of the occurrence of dangerous states.

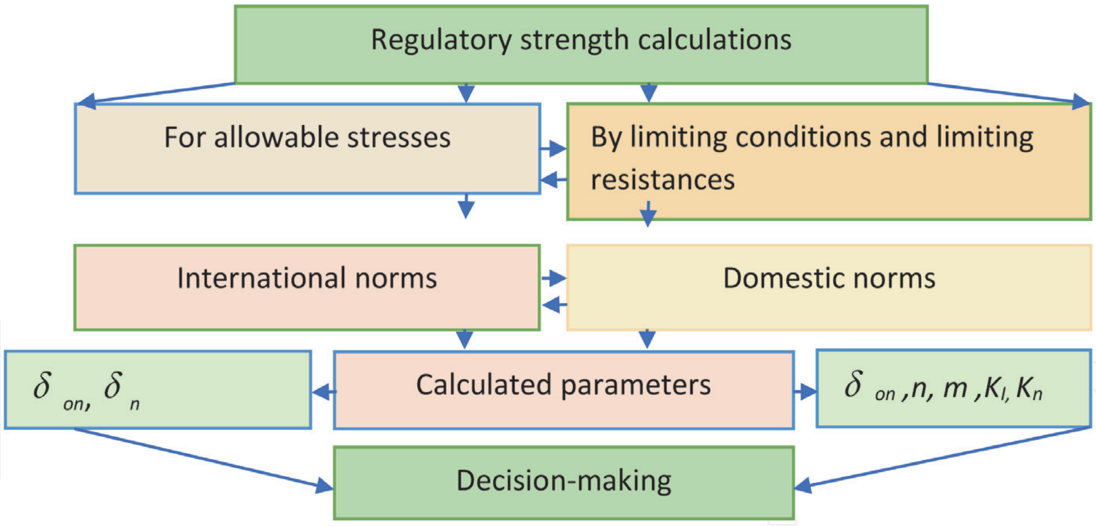

Figure 7.
Block diagram of regulatory foreign and domestic calculations.

The scientific basis of these calculations is the entire system of calculation expressions (1)–(42) (**Figure 7**).

This system has been and remains basic in all international practice [1–4] to the present time with the development of methods for the design, construction, and operation of trunk pipelines to ensure their strength and deformability expressed in a gradual decrease in margins n ($1.8 \geq n_T \geq 1.2$; $2.5 \geq n_в \geq 1.7$) и and an increase in the strength characteristics $\sigma_Т, \sigma_В$ ($200 \leq \sigma_T \leq 800$; $420 \leq \sigma_в \leq 920$ MPa).

All uncertainty factors included in the calculations and reflecting the operating conditions, design, and construction technologies were taken into account by the coefficients (n_σ, n_T, $n_в$) and the standard purpose of guaranteed mechanical properties ($\sigma_В, \sigma_Т$).

A generalized analysis of trends and parameters of the development of pipeline transport of oil and oil pipelines and methods for calculating the strength is made in [6, 7].

Expressions (1) and (2) are initial in assessing the strength of pipelines at all the main stages of the life cycle—design, construction, operation, and decommissioning. Currently two tasks are being solved:

- The direct task of a deterministic basic calculation of the wall thickness δ of the pipeline at the design stage with a preliminary feasibility study of the diameter $D_в$ and pressure p as well as with the selected structural material σ_{on}, $(\sigma_в, \sigma_T)$ and assigned margin n_σ, $(n_T, n_в)$:

$$\delta \geq \frac{pD_в}{2[\sigma]} = \frac{pD_в \cdot n_\sigma}{2\sigma_{on}}. \tag{43}$$

Under these conditions, the wall thickness δ cannot be less than the value calculated by expression (6) (**Figure 8**).

At the stages of construction, operation, and decommissioning on the basis of (43), deterministic calibration calculations are performed with the following objectives:

- Check of permissible operating pressure $[p]$ at specified

$$[p] \leq 2\frac{\sigma_{on}}{n_\sigma}. \tag{44}$$

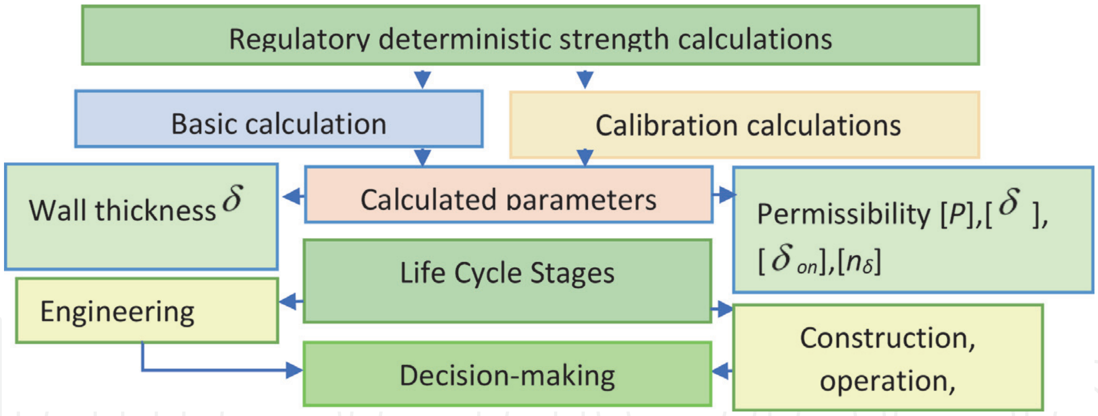

Figure 8.
Regulatory basic and verification calculations for different stages of the pipeline life cycle.

- Validation of selected and assigned mechanical properties σ_{on}, $(\sigma_T, \sigma_{\text{в}})$ with known $p, D_{\text{в}}, \delta, n_\sigma$

$$\sigma_{on} \geq \frac{pD_{\text{в}}}{2\delta} \cdot n_\sigma. \tag{45}$$

- Check by (6) the permissible wall thickness $[\delta]$ at

$$[\delta] \geq \frac{pD_{\text{в}} n_\sigma}{2\sigma_{on}}. \tag{46}$$

- Checking the allowable strength margin$[n_\sigma]$with known

$$n_\sigma \geq \frac{\sigma_{on} \cdot 2\delta}{pD_{\text{в}}}. \tag{47}$$

In deterministic calculations according to (1) and (2), a systematic analysis of uncertainty factors affecting the quantities n_σ, n, m, K_I, and $K_{\text{н}}$ is carried out. These factors [6–10] included such factors as:

- The effect of the absolute dimensions of the sections $(D_{\text{в}}, \delta)$
- Type of stress–strain state (components of the main stress $\sigma_1, \sigma_2, \sigma_3$)
- Temperature–time change in mechanical properties $\sigma_T, \sigma_{\text{в}}$, which determines the processes of aging and degradation
- Availability of welded joints with altered properties

3.2 Databases for calculations

On the basis of statistical measurements and estimates of all specified design parameters (pressures p, mechanical properties $\sigma_T, \sigma_{\text{в}}$, geometrical dimensions δ and $D_{\text{в}}$ with variations within {min, max}), first of all, the determination of their average (median) values becomes important

$$R_{\text{п}m} = \frac{1}{n_{\text{п}}} \sum R_{\text{п}i}, \tag{48}$$

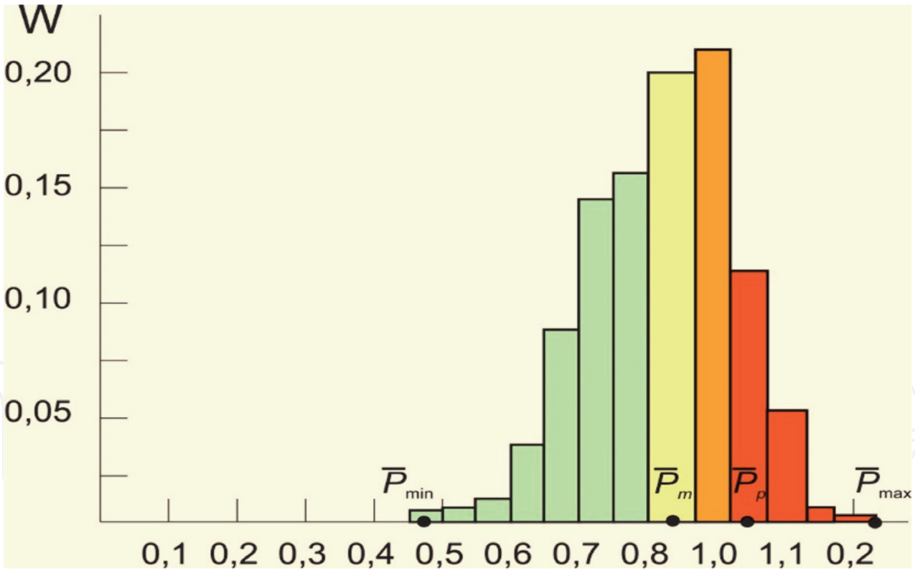

Figure 9.
Histograms of pressures and strengths.

where $n_{\text{п}}$ is the number of measurements of calculated parameters $R_{\text{п}i}$.

According to the obtained statistical information on the parameters R_{ni}, the corresponding histograms are constructed by the intervals of their values. For example, **Figure 9** shows the change in the main design parameters—pressure p and ultimate strength $\sigma_{\text{в}}$ [10].

Inequality (47) with the parameters included in it, as well as the data from **Figure 9**, are the basis for calculating the determination of R_p taking into account the statistical and probabilistic dispersion characteristics. At the same time, the assigned parameters R_p should correspond to the inequality systems

$$P_{\min} \le P_m \le P_p \le P_{\max} \tag{49}$$

$$\{\sigma_T, \sigma_{\text{в}}\}_{\min} \le \{\sigma_T, \sigma_{\text{в}}\}_p \le \{\sigma_T, \sigma_{\text{в}}\}_m \le \{\sigma_T, \sigma_{\text{в}}\} \tag{50}$$

$$D_{\min} \le D_m \le D_p \le D_{\max} \tag{51}$$

$$\delta_{\min} \le \delta_p \le \delta_m \le \delta_{\max} \tag{52}$$

For the design stage, statistical analysis of the design parameters using expressions (8)–(12) is done using factory test data for sheet blanks for pipes (δ), pipes (δ, D), and laboratory samples for static tension ($\sigma_{\text{T}}, \sigma_{\text{B}}$).The values obtained δ_p, D_p, $(\sigma_{\text{T}}, \sigma_{\text{B}})_p$ are entered in the technical conditions or standards. They are the basis of deterministic calculations.

If these measurements are carried out at the stage of construction or operation, then the data obtained from (49)–(52) are included in deterministic calibration calculations and expressions (44)–(47) (**Figure 10**).

Technical diagnostics of trunk pipelines (mainly using in-line diagnostics [11]) shows that the most significant from the point of view of strength is the decrease in time τ wall thickness parameters δ due to such processes as uniform and uneven corrosion, formation and development of cracks of corrosion, and cyclical nature. These processes, as a rule, increase the variation of values δ in (52).

The statistical variation of diameters in (11) at the stage of manufacturing, construction, and operation of the linear part of trunk pipelines is small ($0.99 \le D_{\text{в}}/D_m \le 1.01$) and can be neglected in deterministic and statistical strength calculations according to (1). However, if during operation there are significant reductions in wall thickness δ, then a significant local increase in diameter $D_в$ (by 5–10 due to plastic deformations with the formation of shape defects) is possible. Similar processes of loss of shape and increase in $D_в$ are possible with nonstandard bending of pipelines with loss of stability and formation of corrugations.

The change in the average values and variation of the design characteristics of strength (σ_B, σ_T) according to (50) is associated with the instability of technological processes for the production of pipe steels, rolling and heat treatment of sheets, pipe manufacturing, construction of pipeline systems, as well as temporary processes of aging and degradation.

Figures 11 and **12** show histograms and distribution functions of the mechanical properties of a long-term (up to 50 years) operated 17G1S tubular steel. This information is used in the implementation of calculations for paragraphs 2.1–2.3.

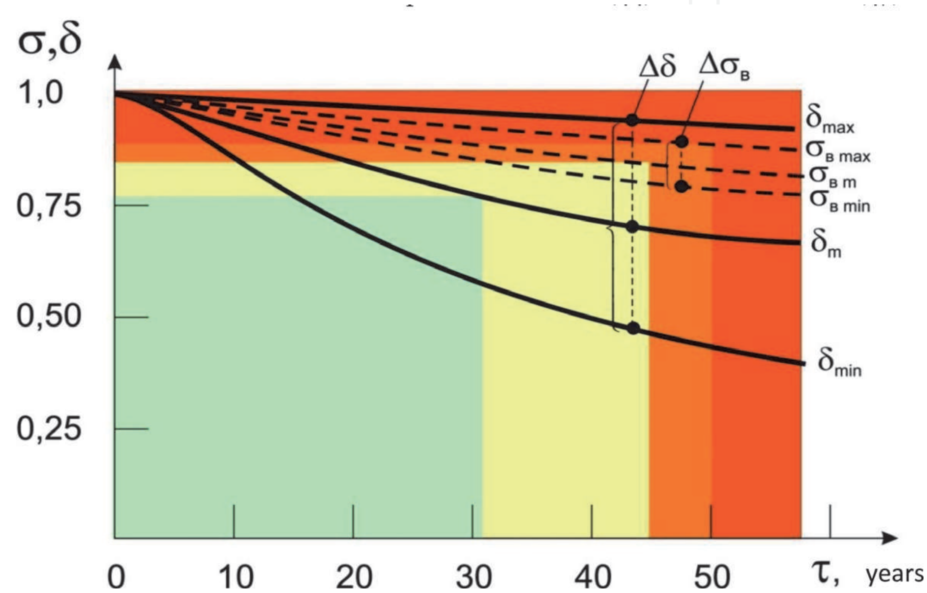

Figure 10.
Statistics on the relative decrease or increase in operating time.

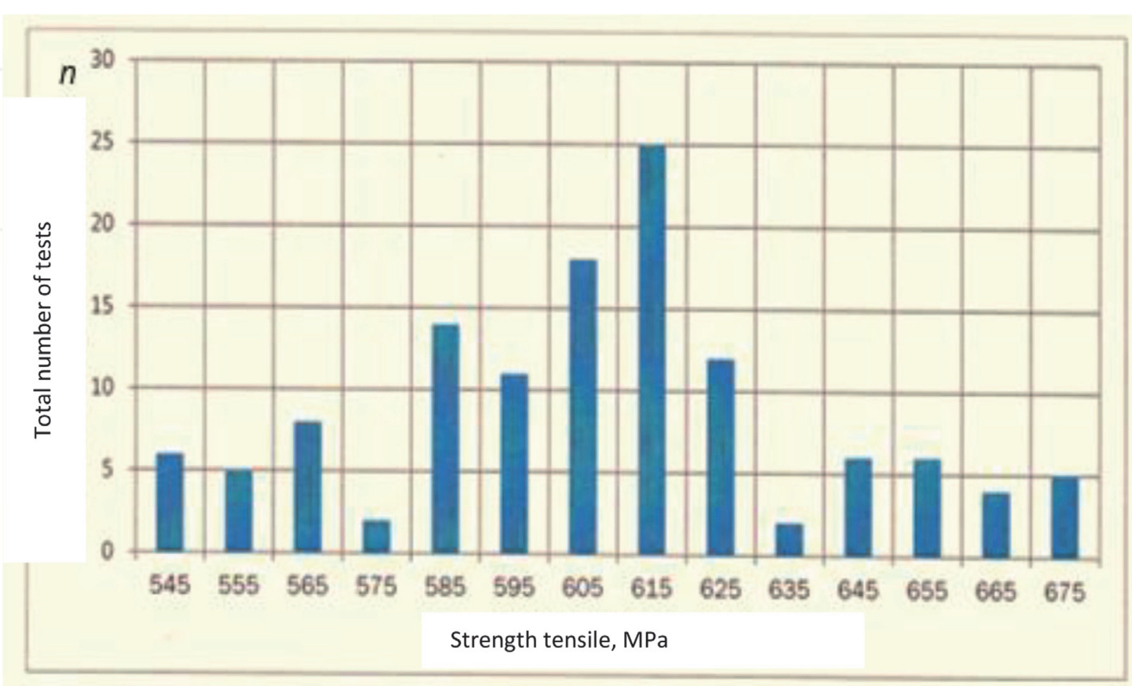

Figure 11.
Strength tensile histograms $\sigma_в$ (total number of tests n = 160).

In the process of development (in time τ) of pipeline transportation of hydrocarbons in Russia and abroad, three trends remain dominant using deterministic (D), statistical (C), and probabilistic (P) methods (**Table 1** and **Figure 13**).

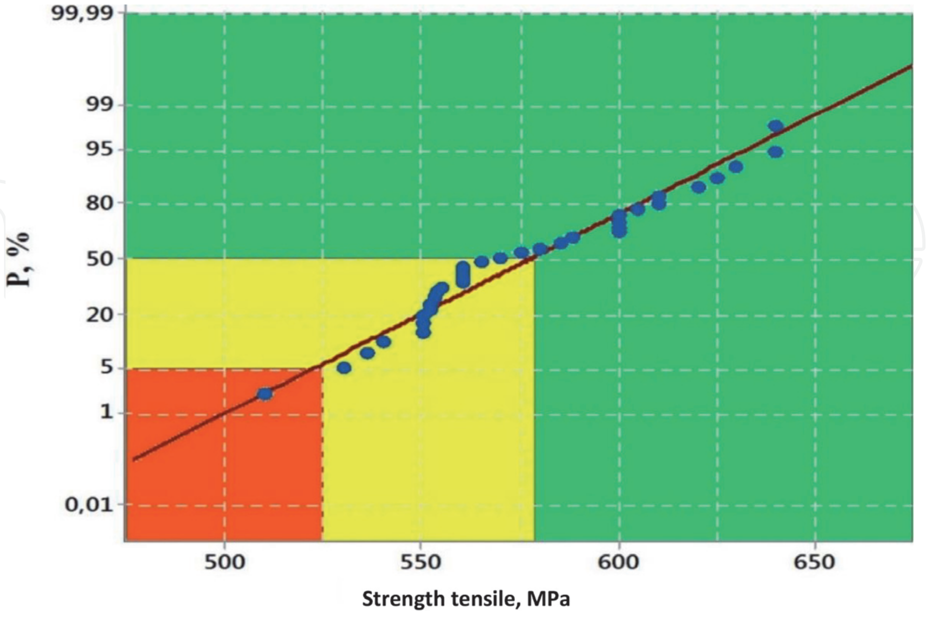

Figure 12.
Distribution function of the ultimate strength of pipe steels 17G1S.

No.	Description	Symbols	Value
1.	Coefficient of working conditions	m	0.6–0,9
2.	Load reliability factor	K_1	1.1–1,5
3.	Material reliability factor	K_2	1.34–1,55
4.	Reliability factor to destination	$K_н$	1.0–1,05

Table 1.
Calculated standard values of coefficients.

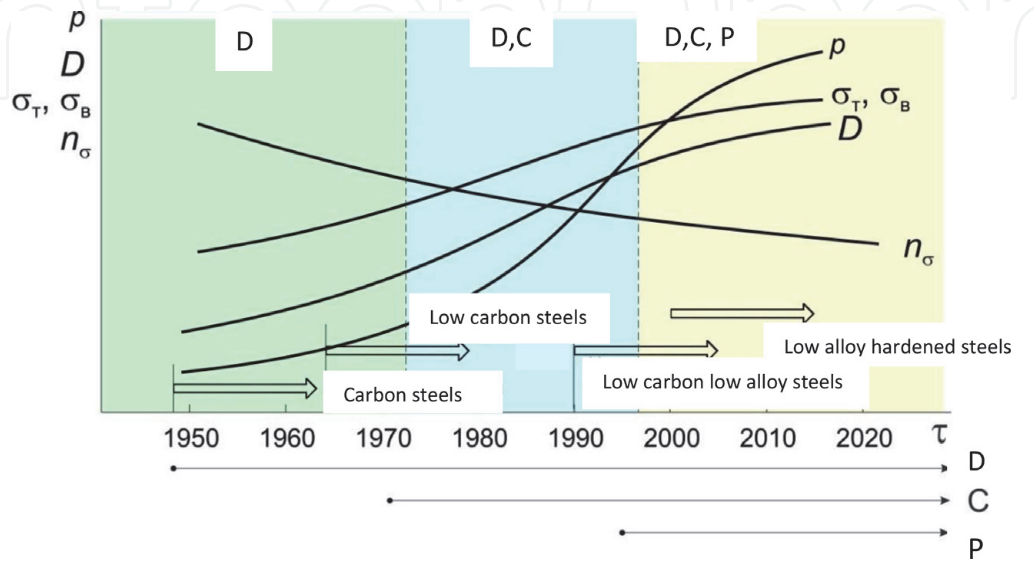

Figure 13.
The main regularities of changes in the estimated parameters of pipelines.

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

- Increase of mechanical properties of pipe hoists (yield strengths σ_T) from 200 to 250 МПа to 600 to 800 MPa and strength σ_u from 400 to 450 MPa to 700 to 900 MPa

- Reduction of strength margins n_T (от 1.8–3,2 до 1.2–1,5) and n_u (от 2.4–3,5 до 1.6–1,8) in expression (3) and the estimated coefficients in expression (5)

4. Conclusion

The above data (pp. 1–3) allow you to build a comprehensive strength analysis system using deterministic, statistical, and probabilistic methods for various components, taking into account design, technological, and operational factors.

Deterministic strength calculations are used as part of regulatory national and international approaches for design calculations. They apply to the majority of functioning oil pipelines systems.

Statistical calculations become relevant in cases where during operational process the diagnostic studies of the condition of pipelines are carried out or during construction routine tests and during operation defects of technological and operational origin are detected. Probabilistic calculations are necessary on the most dangerous sections of the pipeline (in case of crossing water barriers, transport infrastructures, and laying offshore pipelines).

In all cases, safety margins are linked to the normative standard documentation (deterministic approach), the results of diagnostics and defect identification and measurement (statistical approach), and taking into account the most dangerous operating conditions (probabilistic approach).

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