Creating the knowledge base and data banks to justify the strength reliability of the pipeline transport system for oil and petroleum products

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ABSTRACT

The paper outlines the scientific fundamentals for creating and applying the knowledge bases and the data banks in the design, construction and operation of pipeline transport systems. The analysis of knowledge is carried out, the main directions of knowledge base creation and its fundamentals are considered in terms of the pipeline transport of oil and petroleum products. The knowledge bases include both the existing system of scientifically validated proposals to the structure, classification, criteria, constitutive equations for design-and-experimental assessment of strength, stability, stiffness of the load-bearing elements of pipeline transport facilities, and further development of these proposals in terms of analyzing the operation life, reliability, and damage tolerance of the pipeline transport system, analysis of its protection against crisis and emergency situations. Data banks are considered as the initial information basis for the knowledge implementation at all stages of the pipeline transport system life cycle. It is concluded that the creation of the unified system of knowledge base and data banks is of significant scientific and practical importance for the further development of pipeline transport systems with regard to up-to-date requirements for ensuring and improving their strength, service life, reliability, damage tolerance, and safety of construction and operation.

Key words: knowledge base, data bank, strength, stability, stiffness, operation life, service life, reliability, damage tolerance, safety, protection, risk, pipeline transport, legislation, regulations.

INTRODUCTION

The knowledge base shall be understood as the systematic integrated information accumulated in the process of scientific fundamental and applied studies on the governing principles of evolution, on the criteria and equations for methods to analyze functioning of a complex social-natural-technogenic (S-N-T) system in order to achieve the aimed parameters in the relevant sphere of life activities and life support. The knowledge base becomes an important and integral component of intellectual, scientific, technical, and socio-economic activities of a person, society, and the state. The key requirements to the knowledge bases are scientific validity, reliability, and applicability to new knowledge gain and practical use.

The data bank shall be understood as the system of specially created, organized and implemented information traffic and a set of specific information environment that are necessary for the evolution and implementation of knowledge bases when solving applied problems in the relevant areas of scientific and practical activity. The key requirements to the data banks are: relevance, sufficiency, reliability, completeness, orientation, and suitability for collecting, storing, processing, and using the information.
Knowledge bases and data banks are now becoming increasingly important in the advanced fields of science and technology. In fact, they are the basis for the development of artificial intelligence technologies, namely knowledge engineering, which practically is a field of science related to the development of expert systems and knowledge bases. The artificial intelligence technologies evolution is the most promising and important scientific and technical task of all countries. Thus, if 5 countries adopted the national strategy for the artificial intelligence development in 2017, then already 30 countries have adopted it in 2018–19. In Russia, a draft national strategy for the development of artificial intelligence was also developed in 2019.

As a rule, the knowledge bases are generated in the leading academic and R&D institutes, and data banks – in the industry-specific scientific, design, and technological organizations. Knowledge bases and data banks are also relevant in pipeline transport, including oil and petroleum products.

Since the second half of the 20th century, the pipeline transport of hydrocarbons (PTHC), gas (PTG), oil and petroleum products (PTOPP), in terms of its significance has come to the front in the country’s life support infrastructures. Concepts and strategies of national security1, science and technology progress2, legislation in the area of security3,4, and strategic planning5 determine the scope of tasks relating to operation of existing PTHC systems and construction of new ones. This is reflected in the strategies for pipeline transport development until 2025–30 at the level of ministries (Ministry of Energy, Ministry of Construction, Ministry of Natural Resources, Ministry of Regional Development) and major Russian companies (Transneft, Gazprom, Rosneft, Novatek, Lukoil, etc.).

The scientific support for implementing these strategies in the near and long term shall be provided by academic institutions and leading scientific organizations. At that, the economics of knowledge will be of key importance in our country, combining advanced scientific achievements in fundamental, pilot and applied sciences and up-to-date design and technological solutions for implementing two national priorities – improving the social-economic standard of living, and ensuring national security. These strategic priorities

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1 National security strategy. Approved by the Decree of the President of the Russian Federation of May 12, 2009 No. 537.
2 Strategy for scientific and technological development of the Russian Federation. Approved by the Decree of the President of the Russian Federation of December 1, 2016 No. 642.
3 Federal Law of December 28, 2010 No. 390-FZ ‘On security’ (as amended and supplemented).
4 Federal Law of July 21, 1997 No. 116-FZ ‘On industrial safety of hazardous production facilities’ (revision of 2017).
5 Federal Law of June 28, 2014 No. 172-FZ ‘On strategic planning in the Russian Federation’ (adopted by the State Duma of the Federal Assembly of the Russian Federation on June 20, 2014)
shall be implemented within a combined S-N-T system, considering the development features of its components (S – social, N – natural, T – technogenic). In such a problem statement, creating a unified federal and industry-specific knowledge base and data banks on the main problems of pipeline transport development, and using the best available domestic and foreign practice will become ever more relevant.

The block diagram for knowledge base and data banks creating and subsequent implementing for PTHC is shown in Fig. 1. The focus area in the present work will be PTOPP.

Creating the advanced knowledge base

Analysis of the knowledge status in the pipeline transport

The fundamental studies on S-N-T system evolution principles have been conducted for almost three centuries in our country by the Academy of Sciences (Russian Imperial Academy (RIA), Academy of Sciences of the USSR (AS USSR), Russian Academy of Sciences (RAS)). The results of these studies (Fig. 2) are summarized in published Proceedings of the Academy, a multi-volume academic publication [1], in Great Soviet and Russian Encyclopedias [2, 3], as well as in special publications on national security issues [4]. Legal, social-economic, scientific and technical aspects and relevant knowledge bases on security issues are reflected in the 53-volume series ‘Security of Russia’ [5]. Targeted fundamental and applied knowledge bases on issues of protection against emergencies are contained in encyclopedic publications of the Ministry of Emergency Situations of Russia and the Russian Academy of Sciences [6]. A certain place in works [1–6] is also belongs to the knowledge bases in the general pipeline transport and PTHC (PTG, PTOPP) in particular.

The applied knowledge related to the pipeline transport problems has been accumulated in various sectors of economics, industry and technology, and summarized in multi-volume publications, e.g. in the nuclear power sector [7, 8]. The most complete scientific knowledge bases on a number of important issues of PTHC systems construction and operation are reflected in the monographs of N. P. Aleshin [9], P. P. Borodavkin [10], O. M. Ivantssov and I. I. Mazur [11], Yu. V. Lisin [12], N. A. Makhutov and V. N. Permyakov [13], I. V. Orynyak [14], B. E. Paton [15], O. I. Steklov [16], S. A. Timashev [17], V. V. Kharionovsky [18].

The results of fundamental studies and applied R&D were the platform for creating a concentrated knowledge base, which was included in the system of legal and regulatory-technical documents of the federal, industry-specific and facility-specific levels (in federal laws, norms and rules, strategies, standards, regulations, regulatory-technical documents of companies and enterprises).

Currently, a number of leading organizations in the country have started developing pilot versions of the knowledge base on key issues of science, technology and industry. In particular, PJSC Transneft has created and effectively operates a knowledge management system (KMS) for automated process control systems (APCS). The Institute of Machine Science of the Russian Academy of Sciences is creating a knowledge base in strength, operation life, reliability and safety of technosphere facilities [19].

PJSC Transneft and its leading R&D Pipeline Transport Institute LLC have every reason to use their accumulated expertise to start working in order to create a targeted multi-level and multi-component knowledge base in order to improve the level of scientific, technical and social-economic...
justification of strategies, programs and plans to develop the trunk PTOPP systems.

Mainstreams in the PTOPP knowledge base creating

When creating the PTOPP knowledge base, it is advisable to proceed from a certain structure and the relevant mainstreams list [20]. There are two possible options here:

- using and development of the traditional ‘from simple to complex’ evolution approach matured at the previous stages, which is characterized by increasing demands to strength, durability, reliability, and damage tolerance of PTOPP facilities (Fig. 2);
- creating a new knowledge base focused on the new integrated requirements of the state to PTOPP in terms of safety and protection against crises, failures, accidents and disasters with regard to social-economic and natural-technogenic risks of various levels (from facility-specific to strategic ones).

The second option is more promising until 2025–30, however it requires in the process of its implementation to apply the results of works performed in accordance with the first option, as well as fundamental Federal documents\(^6\), and a set of internationally recognized documents. These include first of all the UN framework program for natural disasters risk reduction until 2030 (‘Hyōgo-2’)\(^11\) that defines as a top priority the broadest understanding of risks – from personal to national and global.

The most significant for a new PTOPP knowledge base creating are the materials published in works [5, 11–14, 16, 18].

The knowledge base structures created according to the second option may include the following key components (Fig. 3):

- A conceptual framework in the analysis of general problems of PTOPP development, considering both officially accepted interdisciplinary and interindustry definitions, and special ones contained in the documents of PJSC Transneft, with picking key concepts and definitions – a new hierarchy of requirements for PTOPP construction and operation in accordance with the above-mentioned fundamental Federal documents.

- A new approach to ranking PTOPP facilities by hazard levels (global, national, regional, territorial, facility-specific, local) when they function in the S-N-T system with regard to human, natural and technogenic factors at all stages of the life cycle.

- A ‘top-down’ PTOPP systems ranking by all major components criticality.

- A structure of scenarios, design cases, and analytical models for PTOPP systems, their components and life cycle stages, considering design, off-design, beyond-design and hypothetical emergencies.

- A unified system of differentiated and integrated criteria for making science-based decisions on the development of concepts, strategies, programs, plans, feasibility studies, technical assignments, front-end and detailed engineering, expert reviews and opinions on PTOPP facilities.

- A unified system of limit states, constitutive equations and their parameters for quantitative design-and-experimental assessment, time-and-cost valuation rating, regulation, and supervision of PTOPP facilities compliance with established requirements.

- A generalized structure and set of requirements to data banks for implementing knowledge bases when constructing scientifically validated new PTOPP facilities and extending the service life of operating facilities with acceptable risks.

Fundamentals of PTOPP knowledge base

Social and economic aspects of the knowledge base

According to the Federal requirements\(^2\),\(^3\),\(^4\),\(^5\),\(^6\),\(^7\),\(^8\),\(^9\),\(^10\) and with regard to the strategic priorities – improving the social-economic standard of living and ensuring national security, the following social and economic characteristics are of key importance in the knowledge base on PTOPP issues:

- economic indicators of the pipeline transport system functioning over time \(\tau\) in the form of PJSC Transneft gross product \(V(\tau)\), which is an integral part of the country’s gross domestic product;
- preservation of life and health of operators, personnel and the population \(N(\tau)\) in standard and emergency situations of PTOPP facilities operation.

As a rule, the estimated and actual indicators of the country and the industry progress that use traditional approaches, strategies and concepts of development do not directly give consideration to the potential and emerging risks \(R(\tau)\). Such consideration is proposed by authors [5] in the form of decreased \(F(\tau)\) and \(N(\tau)\) due to risks \(R(\tau)\), economic damage \(U_{\tau}(\tau)\) and loss of human lives \(U_{\nu}(\tau)\) while implementing hazardous, crisis, emergency and catastrophic processes:

\[
V_{\nu}(\tau) = V(\tau)[1 - R_{\nu}(\tau)],
\]

\[
N_{\nu}(\tau) = N(\tau)(1 + \Delta N(\tau))[1 - R_{\nu}(\tau)],
\]

\(^{6}\) National security strategy of the Russian Federation;
\(^{7}\) Strategy for scientific and technological development of the Russian Federation;
\(^{8}\) Federal Law No. 390-FZ;
\(^{9}\) Federal Law No. 116-FZ;
\(^{10}\) Federal Law No. 172-FZ;
\(^{11}\) Sendai framework program for disaster risk reduction in 2015-2030, adopted at the Third World conference in Sendai (Japan) on March 18, 2015.
Where:

\[ V(t), N(t), V_s(t), N_s(t) \] – progress indicators without and with regard to economic \( R_e(t) \) and social \( R_s(t) \) risks.

\[ \Delta V(t), \Delta N(t) \] – gross domestic product and population growth rates, respectively.

Risks \( R_e(t) \) and \( R_s(t) \) are defined as relationships

\[
R_e(t) = \frac{U_e(t)}{V(t)}, \quad (3)
\]

\[
R_s(t) = \frac{U_s(t)}{N(t)}, \quad (4)
\]

Where:

\( U_e(t) \) – economic damage

\( U_s(t) \) – loss of human lives.

The component \( U_e(t) \) includes economic damage (losses) for the entire S-N-T system. Social losses include damage from non-natural and premature loss of human lives, natural losses – damage from impact, pollution and destruction of environmental compartments, technogenic losses – damage from failures, accidents, and catastrophes at PTOPP facilities.

All values in expressions (1)–(4) refer to the time interval \( \Delta t \) equal to 1 year and are considered as annual. To ensure the sustainable development of PTOPP in the estimate time interval from initial \( t_0 \) to final \( t_f \), it is necessary for \( V_s(t) \) and \( N_s(t) \) values to grow \( (t_0 \leq t \leq t_f) \), and for \( U_e(t) \) and \( U_s(t) \) losses, as well as for \( R_e(t) \) and \( R_s(t) \) risks to decrease:

\[
V_s(t_f) \geq V_s(t_0), U_e(t_f) \geq U_e(t_0), \quad (5)
\]

\[
R_e(t_f) \leq R_e(t_0), R_s(t_f) \leq R_s(t_0), \quad (6)
\]

It means that the annual economy’s growth rate \( \Delta N(t) \) shall be higher than economic risks \( R_e(t) \) growth rate:

\[
\Delta V(t) \geq R_e(t), \quad (7)
\]

\[
\Delta N(t) \geq R_s(t). \quad (8)
\]

Expressions (1), (3), (5), (7) characterize the economic component in solving the first strategic priority (improving the social-economic standard of living), and expressions (2), (4), (6), (8) characterize the social component (Fig. 1).

The entire system of expressions (1)–(8) with regard to risk factors \( R_e(t), R_s(t) \) characterizes the status and evolution of developments for ensuring safety at the national, regional, industrial, facility-specific and individual levels.

The knowledge base analyzing the current and long-term activities of PJSC Transneft and Pipeline Transport Institute LLC shall include the main structural components of the PTOPP knowledge base (Fig. 3).

**Knowledge bases on risks, protection and safety**

According to expressions (1) – (8), priorities and goals of evolution (Fig. 1) are linked to generation and implementation of risks \( R(t) \) at every stage \( t \) of the life cycle for PTOPP facilities and management structures being created and operating with regard to requirements\(^{17,18,19,20,21}\) and initial data from reference [5].

Generally speaking, risks \( R(t) \) shall be understood as the function of two key parameters:

- occurrence probability (frequency) \( R(t) \) of contingencies, adverse processes, events, phenomena (hazards, crisis, threats, damages, failures, emergencies, disasters);
- damage (losses) \( U(t) \), accompanying these processes, events, phenomena.

\[
R(t) = F_s\{P(t) \cdot U(t)\}. \quad (9)
\]

The expression (9) is crucial for the conceptual and

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**Figure 3.** Block diagram for the knowledge base on the PTOPP issues.
quantitative definition of risks. In the simplest form, the function $R_i$ in (9) for $i$-th event is represented as

$$R_i(\tau) = P_i(\tau) \cdot U_i(\tau).$$

(10)

For a number of related and unrelated events $n (1 \leq i \leq n)$, risks $R(\tau)$ may be summarized using (9) and (10):

$$R(\tau) = \sum_{i=1}^{n} \{ P_i(\tau) \cdot U_i(\tau) \}.$$ (11)

For complex PTOPP systems and complicated scenarios of their operation in presence of analytical correlation between $P(\tau)$ and $U(\tau)$, an integration may be performed in order to assess the integral risks. The scientific fundamentals of risk analysis and safety problems are described in special four volumes of the ‘Security of Russia’ series [5]. At that, the baseline includes statistical or stochastic dependencies between probabilities $P(\tau)$ of contingencies and accompanying damage (losses) $U(\tau)$ (Fig. 4).

These relationships for a number of facilities are close to power laws.

$$P_i(\tau) U_i^{-m_i}(\tau) = C_i,$$ (12)

Where:

$m_i$ – exponent $0.2 \leq m_i \leq 0.5$.

The constant $C_i$ depends on the type and purpose of the pipeline transport.

For PTG and PTOPP systems, the extensive information has been acquired domestically and globally on the probability $P(\tau)$ gradual decline in time $\tau$ for pipelines' failures, damages and fractures per 1000 km/year (Fig. 5). This was facilitated by a whole range of design, technological and operational activities. The approximation of $P(\tau)$ versus $\tau$ shows the acceptability of using a power or exponential equation in the analysis of pipeline transport safety.

At the first stage of creating knowledge bases, one can use a power relationship

$$P(\tau) \tau^{-m_c} = C,$$ (13)

Where:

$m_c, C$ – constants of the pipeline system.

For PTOPP, $m_c$ exponent is approximately 0.40–0.45. In total, maximum direct damage $U_{max}(\tau) = U_K(\tau)$ from the most severe accidents in pipeline transport, which had a national character (for example, the accident in 1989 near Ufa with the destruction of two passenger trains with people), can attain hundreds million and billion rubles. And considering the indirect damage associated with repair and rehabilitation works and charging compensation and insurance payments, they may be 1.5-2.5 times higher.

Variations of probability $P(\tau)$ for severe disasters are in the range of tenths and hundredths of unity, while the values of the risks of accidents $R^\theta(\tau)$ at a given stage of pipeline transport operation taking into account the costs of inspection and repair can be at least hundreds of millions of rubles per year.

Introducing risk margins, then:

$$R(\tau) = [R(\tau)] / n_r,$$

(14)

with the destruction of two passenger trains with people).

Figure 4. Correlation between probability and damage of contingencies.

Figure 5. Trend of accident rate changes in the pipeline transport system by year.

17 National security strategy of the Russian Federation;
18 Strategy for scientific and technological development of the Russian Federation;
19 Federal Law No. 390-FZ;
20 Federal Law No. 116-FZ;
21 Federal Law No. 172-FZ;
Where:

\[ R_{1}(\tau) \] – maximum unacceptable risks that characterize the most severe cases of emergency situations

\[ [R(\tau)] \] – acceptable risks for this stage of the pipeline transport operation.

Expression (14) is the main tool to assess safety \( S(\tau) \).

The level of protection \( Z(\tau) \) of PTOPP facilities against dangerous situations is estimated by the difference between actual \( R(\tau) \) and acceptable risks:

\[ Z(\tau) = [Z(\tau)] - [R(\tau)] - R(\tau) \geq 0. \] (15)

In accordance with expression (15), when constructing and operating PTOPP, it is necessary to ensure that the entire protection system is in the zone of acceptable risks \([R(\tau)]\), meeting the safety requirements in (14).

If one accepts \( R_{1}(\tau) = U_{\text{max}}(\tau) = U_{1}(\tau) \) and \( n_{h} \) value at specified level \( (n_{h} \geq 1) \), then acceptable risks \([R(\tau)]\) may be fixed by (14).

Managing risks, safety and protection

Currently, inequality \( R^{\text{pr}}(\tau) > [R(\tau)] \) is satisfied in our country and overseas in a number of cases, therefore a set of actions shall be implemented in the coming years to reduce risks \( R^{\text{pr}}(\tau) \) to an acceptable level \([R(\tau)]\) with annular costs \( Z_{h}(\tau) \):

\[ Z_{h}(\tau) = \frac{1}{m_{\text{ke}}} \left( R^{\text{pr}}(\tau) - [R(\tau)] \right), \] (16)

Where:

\( m_{\text{ke}} \) – cost-effectiveness ratio.

Regarding the advanced technology practice [5], \( m_{\text{ke}} \) values for PTOPP may be taken as:

\[ 1 \leq m_{\text{ke}} \leq n_{h} \] (17)

At the present stage of PTOPP evolution, the set of actions aimed at reducing risks to an acceptable level, ensuring safety and protection with regard to expressions (9), (14), (15), (16), (17) shall include as a priority the R&D works and scientific justifications of the Pipeline Transport Institute LLC with costs \( Z_{h}^{\text{ke}}(\tau) \):

\[ Z_{h}^{\text{ke}}(\tau) = K^{\text{ke}} Z_{k}(\tau), \] (18)

The cost ratio for these works and justifications during 2018-2020 can be assumed at the level of 0.3 – 0.4. The cost of creating knowledge bases and data banks during this period may be estimated as:

\[ Z_{k}^{\text{ke}}(\tau) = K^{\text{ke}} Z_{k}(\tau) \] (19)

The cost share value \( K^{\text{ke}} \) may be taken equal to 0.05 – 0.1.

Based on expressions (1) – (19), when developing and implementing PTOPP evolution programs and plans with regard to the up-to-date requirements23,24,25,26 and results of theoretical and practical works [5], it is necessary to analyze the acceptable damage \([U(\tau)]\), probability \([P(\tau)]\) and operation time \([\tau]\) of main structures and facilities with regard to the relevant acceptable areas of application (Fig. 4 and Fig. 5).

To implement such approach in PTOPP evolution programs and plans, using expressions (1) – (8) with regard to (9) – (13) and (14), (15), (16), the estimations shall be performed to justify the necessary actions and values \([P(\tau)]\), \([U(\tau)]\), \([R(\tau)]\), \([Z(\tau)]\) for assessing within acceptable limits the levels of safety \( S(\tau) \) from (14) and protection \( Z_{h}(\tau) \) from (15). These actions require the relevant scientifically proven costs \( Z_{h}(\tau) \) to reduce risks per (16), costs \( Z_{h}^{\text{ke}}(\tau) \) to perform R&D works and costs \( Z_{h}^{\text{ke}}(\tau) \) to create knowledge bases.

Integral fundamentals of knowledge bases to ensure PTOPP safety and protection using risk criteria

The fundamental key criteria to construct and operate PTOPP system with regard to abovementioned baseline Federal documents are its safety \( S(\tau) \) and protection \( Z(\tau) \) against dangerous processes, events and phenomena. Values \( S(\tau) \) and \( Z(\tau) \) shall be determined in compliance with the entire system of expressions (1)–(19) with inclusion of three risk groups – generated \( R(\tau) \), critical \( R(\tau) \) and acceptable \( R(\tau) \) into expressions (1)–(11), (14)–(16).

According to references [5, 20, 21] values of these risks \( R_{1}(\tau) \) by (9)–(11) include two main parameters (Fig. 4 and Fig. 5):

- probability (frequency) \( R(\tau) \) of adverse and dangerous processes, events, phenomena
- corresponding damage (losses) \( U(\tau) \).

Since PTOPP is one of the components of a complex S-N-T life support system, \( P(\tau) \) and \( R(\tau) \) generally shall be determined with regard to social (human \( h \), natural \( n \) and technogenic \( t \)) factors:

\[ R(\tau) = F_{h} \left\{ R_{h}(\tau), R_{n}(\tau), R_{t}(\tau) \right\}, \]
These factors shall be considered when forming PTOPP evolution programs and plans based on expressions (1)–(8), (14)–(19).

Currently, much attention is paid domestically and globally to the problems of technogenic safety and protection against technogenic failures, accidents and disasters, caused by damages and fractures of PTOPP load-bearing elements. The main sources and causes of PTOPP technogenic accidents and disasters are:

- dangerous uncontrolled release of energy \( E(\tau) \), mechanical, thermal, shock, acoustic
- dangerous uncontrolled releases of hazardous substances \( W(\tau) \), oil and petroleum products into the natural environment (air, soil, water)
- dangerous disruption of information flows \( I(\tau) \) in systems for the pipeline systems condition monitoring, management and control.

Then, similar to (20), one can write:

\[
P(\tau) = F_p \left\{ R_h(\tau), R_n(\tau), R_t(\tau) \right\},
\]

\[
U(\tau) = F_u \left\{ U_h(\tau), U_n(\tau), U_t(\tau) \right\}.
\]

In expressions (20), (21), human (h), natural (n) and technogenic (t) factors are the main (sources and causes) in terms of failures, accidents and disasters with damage (losses) to human beings \( U_h(\tau) \), nature \( U_n(\tau) \) and technosphere \( U_t(\tau) \) at relevant probabilities \( P_h, P_n, P_t \). At the same time, the human factor is included in the analysis not only as the source and cause of the dangerous and adverse situations occurrence and escalation, but also as the main factor in ensuring safety \( S(\tau) \) and protection \( Z(\tau) \) occurrence and escalation of accidents and disasters:

\[
\left\{ S(\tau), Z(\tau) \right\} = F_{RN} \left\{ R_h(\tau), R_n(\tau), R_t(\tau) \right\}.
\]

The natural and technogenic factors in (20) appear as sources of dangerous PTOPP damages and impacts in the natural and technogenic living environment.

The unique threefold role of the human factor in the S-N-T system, as a source, victim, and protector against dangerous and adverse processes and phenomena (failures, accidents, and disasters) makes it necessary and mandatory to take it into account in PTOPP evolution programs and plans. These circumstances are not yet explicitly reflected in Federal documents or in industry-specific PTOPP evolution programs and plans. In summing up and applied R&D works [5, 13, 20, 21] on protection \( Z(\tau) \), safety \( S(\tau) \) and risk \( R(\tau) \) issues, the authors propose to construct 3D surfaces of current (formed), limit and tolerance conditions of PTOPP as one of the components of the complex S-N-T life-support system in accordance with expressions (14) – (16), (20) – (22). These surfaces (Fig. 6) are plotted in quantitative coordinates according to the categories (levels) of k-hazards and risks of the analyzed situations for the entire S-N-T system:

1. local emergencies (crisis phenomena and damages) that are typical for certain critical zones of elements of the technogenic, natural and social spheres, when the damage consequences affect the functioning of the facility elements
2. facility-specific emergencies involving damage and impact to the analyzed facility in technogenic, natural and social spheres with consequences within the facility battery limits
3. territorial emergencies that cause damage and impact to the analyzed facility with consequences that go beyond the facility battery limits
4. regional emergencies and catastrophic situations with impact of S-N-T system and subsystems (N-T, T-S, N-S), when consequences of damage and impact violate the life-support conditions in the regions (or industry sectors)
5. national emergencies and catastrophic situations within the above-mentioned subsystems and the entire S-N-T system, when the consequences of impacts violate the country’s life-support conditions
6. global emergencies and catastrophic situations in S-N-T system, when the consequences of impacts

Figure 6. 3D surfaces of safe, limiting, and acceptable PTOPP states.
affect the life-support conditions of the country and neighboring states.

7. Planet-scale emergencies and catastrophic situations, when the consequences of catastrophic impacts affect the life-support conditions in the continents and the planet as a whole.

For the given time \( \tau \in [\tau_i, \tau_j] \) the total integral risks \( \mathcal{R}(\tau) \) with i-th scenario and regard to expressions (9)–(11) will be determined by the sum of classified (categorized) risks:

\[
R_{\text{tot}}(\tau) = \sum_{i=1}^{7} R_{\text{c}}(\tau).
\] (23)

For classified risks \( R_{\text{c}}(\tau) \), the following 5 types \( i = 1–5 \) of emergencies and catastrophic situations are subject to analysis (as their category declines):

8. Assumptive (hypothetic) catastrophic situation with the most severe consequences \( U_{\text{c}}(\tau) \), low and difficult-to-determine probability \( P_{\text{c}}(\tau) \) and extremely high-risk \( R_{\text{c}}(\tau) \).

9. Beyond-design catastrophic situation and emergency with severe consequences \( U_{\text{e}}(\tau) \), difficult-to-justify low probability \( P_{\text{e}}(\tau) \) and risk \( R_{\text{e}}(\tau) \).

10. Design emergency with significant values of damage \( U_{\text{d}}(\tau) \), risk \( R_{\text{d}}(\tau) \) and probability \( P_{\text{d}}(\tau) \) of its occurrence.

11. Contingency with moderate values of damage \( U_{\text{c}}(\tau) \), risk \( R_{\text{c}}(\tau) \) and higher probability \( P_{\text{c}}(\tau) \).

12. Operation failure and contingency with low values of damage \( U_{\text{f}}(\tau) \), risk \( R_{\text{f}}(\tau) \) and higher probability \( P_{\text{f}}(\tau) \).

Similar to (23), one can write:

\[
R_{\text{tot}}(\tau) = \sum_{i=1}^{7} R_{\text{c}}(\tau).
\] (24)

For PTOPP, the analysis of the categories 1–6 to hazards and risks \( 1 \leq k \leq 6 \) using the expression (23), and types 1–5 to emergencies \( 1 \leq j \leq 5 \) using the expression (24) shall be performed. The said enables to analyze protection of major accidents and safety \( S(\tau) \) using the risk \( \mathcal{R}(\tau) \) parameters within the ranking system in accordance with Federal Law No. 116 for hazardous production facilities (HPF) (I–IV hazard classes) to technical regulation (FSTR), breakdown of potentially hazardous facilities of technosphere (including PTOPP) into six classes. According to FZ No. 116, they include classes I–IV of HPF. At that, it is proposed in accordance with the resolution of the joint meeting of the Security Council and the Presidium of the State Council of the Russian Federation [22] to select critically important facilities (CIF) from HPF of classes I–II. Damage, destruction or termination of CIF operation leads to violation of normal living conditions of industries or regions of the Russian Federation. With regard to the recommendation of the Parliamentary Commission on the accident at the Sayano-Shushenskaya hydroelectric power plant [23], it is proposed to select strategically important facilities (SIF) that create threats, damages and risks to the entire country.

The relevant classes of PTOPP knowledge base may include the following elements and facilities:

- **FSTR** – parts, components and assemblies of valves, pumps and tanks, and line pipes of pipeline sections
- **HPF** – pipeline sections, tanks, pumps, valves, other arteries (transport, power)
- **CIF** – major trunk pipeline and tank systems with high parameters in areas of high seismicity, landslides, crossings of water bodies and intersections with other arteries (transport, power)
- **SIF** – unique pipeline systems for domestic and export oil and petroleum products supplies to large oil refineries and defense facilities, and offshore pipelines.

Quantitative ranking of PTOPP against risk \( \mathcal{R}(\tau) \) parameters using expressions (20), (21) can be performed using the relative risk indicators \( \bar{\mathcal{R}}(\tau) \) within 1–7 numbers at coordinate axes of limit surfaces (Fig. 6):

\[
\bar{\mathcal{R}}(\tau) = \frac{\mathcal{R}(\tau)}{\mathcal{R}_{\text{max}}},
\] (25)

\[
\bar{\mathcal{R}}(\tau) = \frac{\mathcal{R}(\tau)}{\mathcal{R}_{\text{min}}}
\] (26)

For all facilities (FSTR, HPF, CIF, SIF), the maximum \( \bar{\mathcal{R}}(\tau) \) value in (25), (26) can vary from 1 to 216: for CIF it is 150–216; for CIF – 125–150; for HPF of hazard class I – 80–125, of class II – 60–80; of class III – 27–60; of class IV – 8–27; for FSTR – 1–8.

With regard to the Federal documents repeatedly mentioned above, as well as to references [5, 21, 22, 23], the knowledge base flowchart shall capture the scientific basis of analysis, classification, and ranking of PTOPP facilities:

- by their importance for achieving the strategic priorities of the country progress (Fig. 1)
- by combining the results of fundamental studies and applied R&D works (Fig. 2)
by the conceptual framework and the criterial basis for assessing, valuating and calculating the hazard scenarios for construction and operation of facilities (Fig. 3)

• by drafting and implementing the risk-oriented approaches (Fig. 4 and Fig. 5)

• by the methodology and depth of quantitative determination and control of safety and protection using risk criteria (Fig. 6 and Fig. 7).

Based on the above and taking into account the consolidated structure of the knowledge base on key protection $Z(\tau)$, safety $S(\tau)$ and risk $R(\tau)$ issues (Fig.3), the flowchart for analyzing PTOPP safety and risk parameters is constructed, including knowledge bases on types of facilities (FSTR, HPF, CIF, SIF), classes and types of emergencies (Fig. 7).

Proper implementation of knowledge bases when constructing and operating PTOPP is possible only if the data banks are available for all major expressions (1)–(26).

In order to achieve strategic priorities of the country progress, the knowledge base shall provide for possible evaluation of all key indicators of protection $Z(\tau)$, security $S(\tau)$, risk $R(\tau)$, safe and reliable operation of PTOPP at all stages of the life cycle ($\tau_0 \leq \tau \leq \tau_\infty$), using expressions (1)–(26). The implementation of the knowledge base requires creating the appropriate data banks for expressions (1)–(26) and their parameters. The issue of data banks creating is the subject of special consideration.

Knowledge bases on analysis of stress-strain and limit states

When creating, implementing, and using a knowledge base for protection $Z(\tau)$, safety $S(\tau)$, and risk $R(\tau)$ as the basis by expressions (1)–(26) for PTOPP construction and operation, one shall keep in mind that final $U(\tau)$ damages are the highest when major regional and national disasters occur at CIF and SIF (Fig. 6 and Fig. 7). Extremely high unacceptable risk $R(\tau)$ is associated with extreme $U(\tau)$ damages even with relatively low probability $P(\tau)$ of severe scenarios release. Such assumptive and beyond-design disasters require mandatory quantitative analysis of the final stages of complete destruction of PTOPP load-bearing elements (pipelines, tanks, valves, pumps) [5, 11–13, 21], resulting in spills, fires and explosions. These destructions are the result of various combinations of external and internal operational impacts $Q(\tau)$ with escalating nominal $\sigma^2(\tau)$ and maximum local $\sigma^2_{\text{max}}(\tau)$ stresses and corresponding strains $e^2(\tau), e^2_{\text{max}}(\tau)$.

The design parameters to determine $P(\tau)$ using $\sigma^2(\tau), e^2(\tau)$ values are:

• mechanical impacts $Q(\tau)$
Internal and external pressure $p^3(\tau)$, axial loads $N^3(\tau)$, torques $M^3(\tau)$ and bending moments $M^3(\tau)$.

Geometric shapes and dimensions of dangerous sections of load-bearing elements: wall thickness $\delta$, diameter $D$, bend radius $R$.

Defining expressions of the materials strength theory, rod, plate, and shell theories enable to establish correlation between stress-strain states $\sigma - \varepsilon$, design solutions ($\delta, D, R$) and impacts $Q^3(\tau)$ [15–25]:

$$\begin{align*}
\left\{ \sigma^3(\tau), \varepsilon^3(\tau) \right\} &= F^3(\tau, p^3(\tau), N^3(\tau), M^3(\tau), \delta, D, R), \\
\left\{ \sigma^3(\tau), \varepsilon^3(\tau) \right\} &= F^3\left\{ \frac{\sigma^3(\tau)}{n_0}, \frac{\varepsilon^3(\tau)}{n_0} \right\}.
\end{align*}$$

(27)

Local stresses and deformations are determined using their nominal values with regard to the stress $\sigma_{\alpha}$ and strain $\varepsilon_{\alpha}$ concentration factors:

$$\begin{align*}
\left\{ \sigma^{\alpha}_{\text{max}}(\tau), \varepsilon^{\alpha}_{\text{max}}(\tau) \right\} &= F^{\alpha, \text{nom}}\left\{ \left( \sigma^{\alpha}(\tau) \right), \left( \varepsilon^{\alpha}(\tau) \right) \right\}.
\end{align*}$$

(28)

Using the values of the main and equivalent reduced stress $\sigma^3(\tau)$ and strain $\varepsilon^3(\tau)$, the classical strength theories I-IV (maximum normal stress, maximum strain, maximum shear stress, maximum energy) enable to write analytical expressions for strength conditions as

$$\begin{align*}
\left\{ \sigma_{\alpha}(\tau), \varepsilon_{\alpha}(\tau) \right\} &= F^\alpha\left\{ \sigma_{\alpha}(\tau), \varepsilon_{\alpha}(\tau) \right\}, \\
\left\{ \sigma^3(\tau), \varepsilon^3(\tau) \right\} &\leq F^\alpha\left\{ \sigma^3(\tau), \varepsilon^3(\tau) \right\} = F^\alpha\left\{ \frac{\sigma^3(\tau)}{n_0}, \frac{\varepsilon^3(\tau)}{n_0} \right\}.
\end{align*}$$

(29)

Where:

$\sigma_{\alpha}(\tau), \varepsilon_{\alpha}(\sigma) -$ dangerous stress and strain from standard specimens tests for the relevant limit states;

$\frac{\sigma}{[\varepsilon]} -$ allowable stress and strain

$n_0, n_\varepsilon -$ stress and strain safety margins.

When solving boundary-value problems of stress-strain and limit states based on expressions (27)–(29), sets of mechanical properties for structural materials are introduced into the calculation: elastic modulus $E$, Poisson’s ratio $\nu$, yield strength $\sigma_y$ and ultimate tensile strength $\sigma_u$, reduction in area $\Psi_\alpha$ and stress $S_\alpha$ in the neck at rupture, the material work-hardening index in the nonelastic region $m$:

$$\begin{align*}
\left\{ \sigma, \varepsilon \right\} &= F\left\{ E, \mu, \sigma_y, \sigma_u, \Psi_\alpha, m, S_\alpha \right\}.
\end{align*}$$

(30)

Using expression (28), the following limit states are analyzed: static fracture (using $\sigma_u$ and safety margins $n_\sigma = n_{\sigma_u}$)
occurrence of plastic strains (using $\sigma_p$ and safety margins $n_p = n_2$), occurrence of unacceptable plastic strains (using $\Psi_k$ and safety margins $n_2$). The analysis of these limit states is the essence of the main calculations for stress-strain behavior of PTOPP load-bearing elements and is crucial in the knowledge base [5–19, 21, 24, 25].

The knowledge base includes also the other limit states [5, 11, 13, 14, 18, 21, 24, 25], which are analyzed in terms of verification calculations (Fig. 8).

These limit states include:

- cyclic fracture at a given number of cycles $N_c^\tau(\tau)$
- delayed fracture due to the temperature-time aging and degradation of mechanical properties $\left(E(\tau), \sigma(\tau), m(\tau), S(\tau)\right)$
- corrosion and corrosion-mechanical, biocorrosion, cavitation, and erosion failure due to metal loss and changes in the geometric characteristics of the load-bearing sections $\left(\sigma(\tau), D(\tau)\right)$
- initiation and propagation of local defects (pores, discontinuities, pits) with subsequent transition to microcracks, macrocracks, and fractures at $\ell(\tau) = \ell_s(\tau)$.

These processes determine the damage tolerance of PTOPP facilities.

In accordance with the verification calculations for cyclic strength, the operation life and damage tolerance are determined by the expressions:

$$N_c^\tau(\tau) \leq \frac{N_c^\tau}{n_p},$$

$$\tau^\tau(\tau) \leq \tau_s(\tau),$$

$$\ell^\tau(\tau) \leq \ell_s(\tau),$$

$$\left\{\sigma^\tau(\tau), N_c^\tau(\tau), \tau^\tau(\tau)\right\} =$$

$$= F_{\sigma,N,\tau}\left\{E(\tau), \sigma(\tau), m(\tau), S(\tau)\right\}. \ (34)$$

Regarding the entire system of expressions (27)–(34), the knowledge bases (Fig. 8) include data acquired as a result of:

- mechanical tests using standard laboratory samples with determining all design characteristics of mechanical properties of structural materials and welded joints [5, 9–21, 25–27]
- bench-scale tests of load-bearing elements models [5, 11, 13, 14, 18, 20, 25]
- field tests (pipes, sections of pipes, valves, pumps, tanks) [5, 11, 12, 27].

The knowledge base with its own structure (Figs. 1, 2), key indicators of damages $U(\tau)$, probabilities $P(\tau)$, and risks $R(\tau)$ (Figs. 4, 5), principles of ranking and classifying facilities and their hazards (Fig. 6, Fig. 7), defining expressions (1)–(34) serves as a scientific basis to perform basic and verification calculations (Fig. 8) for all stages of the PTOPP life cycle. It shall be formed on the basis of dedicated R&D works in PJSC Transneft, Federal rules and regulations, national and industry-specific standards, information and technical reference books, guidelines and methodological framework.

Creating data banks to implement the knowledge bases

Regarding the above basics of creating the knowledge base for the PTOPP construction and operation (Fig. 1, Fig. 3), the following systematic data (Fig. 9), corresponding to the defining expressions (1)–(34), shall be included into the data banks:

- specific data on concepts, definitions, terms and designations contained in legal and regulatory-technical documentation (Federal laws, regulations, standards, Federal rules and regulations, industry-specific norms, and guidelines) [2–6, 24, 27]
- systematic data on the PTOPP structure, categories and classes, operation time, operation parameters, length $\left(p, D, \delta, L, \tau\right)$ [9–18, 20, 25, 27]
- summarized data on failure rates, injuries, their periodicity and related damage and risk $R(\tau)$ [1–6, 9, 11–14, 16–18, 21, 26–28]
- summarized data on lists of main requirements to PTOPP in terms of its reliable and safe operation $\left[p, D, \delta, L, \tau\right]$ [2–6, 11, 13, 14, 18, 20–24, 27]
- systematic data on PTOPP operation loads (pressure $p$, axial $N$, transverse $Q$, bending moments $M$, and torques $M_t$, cycles $N$, time $\tau$, temperature $t$) [5, 9–18, 21, 26, 27]
- systematic data on mechanical properties $\left(\sigma_p, \sigma_n, \Psi_k, E, m, S\right)$ and applications of structural materials in deterministic and static approach considering the stages of the PTOPP life cycle [5, 9, 11–18, 20, 26, 27]
- quantitative data on damaging factors of external
and internal impacts of the working and natural environment (corrosion, erosion, cavitation, vibration, biochemistry, electromagnetism, seismic loads) [5, 11–14, 16, 17, 21, 27]

• data on the state of structural materials and welded joints with regard to the effects of aging and degradation [5, 11, 13, 14, 17, 18, 20, 27]

• inline inspection data with regard to the condition of intrinsic and operational defects, as well as their size \( \ell \), shape and location [5, 9, 11–14, 18, 20, 21, 26, 27]

• data on defining expressions (for basic and verification calculations), design models and design cases [5, 11–14, 16, 18, 20, 21, 27]

• systematic domestic and foreign data on limit states and safety margins for strength \( n_s \), strain \( n_s \), operation life \( n_u \) and \( n_c \), crack resistance \( n_c \) [5, 11–14, 18, 20, 21, 27]

• systematic data on acceptable \( [R] \) and non-acceptable \( R \) risks of initiation and escalation of dangerous processes, phenomena and events for all stages of the PTOPP life cycle [5, 11, 13, 21, 24].

• Additionally, data banks may include [5, 9, 11–13, 18, 20, 21];

• characteristics of R&D, design, technological and test centers on studies, support, regulation and improvement of PTOPP functionality

• characteristics of centers for education and training specialists dealing with PTOPP issues

• data on PTOPP innovative solutions, priority and critical technologies.

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The potential for the near-term development of data banks is the creation of distributed databases. A distributed database is a loosely connected network structure, the nodes of which are local databases. It enables to expand the options of sharing remote data, to improve the system reliability, availability, performance, and scalability, and to save money.

Currently, PJSC Transneft has developed and successfully operates the information system ‘Reliability of the line part of the trunk pipeline’, designed to calculate the length and schedule of the line part (LP) and underwater crossings (UC) sections replacement, and of anti-corrosion coatings rehabilitation.

The basis of design justification to the lengths of LP and UC sections replacement and priority replacement in time is the comprehensive (factor) analysis of the trunk pipeline technical condition. It consists of a set of logical procedures and mathematical calculations based on acquisition, analysis and summarizing the initial data on LP and UC sections and the inspection results.

As part of the factor analysis, the results of studies and initial data acquired in various ways are formalized, thus enabling to consider the maximum number of factors that affect the current and forecasted technical condition of the pipeline. The sources of such information are the results of R&D works, inspection data used in full, long-term practice in the trunk oil pipeline (or UC) operation, as well as databases that accumulate the entire array of this information.

For a formalized factors description, Bayesian solutions are used. They are widely used in the transition from ‘a priori’ and conditional probability to ‘a posteriori’ one. The values of the affecting factors are set for equal intervals from the beginning to the end of the section.

Design of the total length and schedule LP and UC sections replacement is based on the initial data obtained by a comprehensive analysis of the technical condition of the trunk oil pipeline, carried out using the operations analysis methods to find optimal solutions under uncertainty based on mathematical simulation and statistical modeling.

Special reference documentation and software engineering have been developed to implement each stage. The developed software enables to use computers for calculating the main operation characteristics and the pipeline technical condition indicators over the entire length of its LP and UC in accordance with the effective regulatory documents. Calculation of LP and UC sections replacement is provided by integration of such information systems as:

• LP and UC defects data bank that contains the information on PJSC Transneft trunk pipelines for oil and petroleum products; defects detected using ‘smart pigs’ and additional inspection tools; results of strength and damage tolerance estimation; information on scheduled and performed rehabilitation works (data bank is available at JSC Transneft-Diascan)

• database on mechanical properties of steels used in the LP and UC construction and operation, which contains data on pipes and mechanical properties of the parent material, welds and flat products for tubes used in the construction and operation of pipelines in the Transneft corporate system; requirements to pipes and rolled products in compliance with interstate and national standards of the Russian Federation, specifications, etc. (available in the Scientific-Technical Center of Pipeline Transport Institute LLC)

• database on the technical condition and reliability of LP facilities, which provides the reliability design and evaluation for oil trunk pipelines’ LP and UC, drafting and feasibility study of administrative and technical activities proposed in the project to improve the LP and UC reliability (available in the
Also, the Pipeline Transport Institute LLC has created a mathematical model to convert pressure data from the distant monitoring and control system (DMCS) to pressure values in each section. Then, using the pressure series, one can determine the normalized cyclicity values. Further, it is planned to design a method and an automated software package to calculate the cyclic loading of trunk pipeline LP sections using DMCS data. The purpose is to improve the system for assessing the operation life of pipes with defects by automated tracking pressure drops and their mapping.

In accordance with the proposed approach, a list of sections was created to be replaced in the period 2017–21 for a number of trunk pipelines in order to ensure the required throughput capacity. At that using the results of this work, the previously planned volume of pipe replacement was reasonably reduced, while the expected pipeline operation reliability was increased with regard to planned higher utilization. At the current stage, the entire list of trunk oil pipelines included in the pipe replacement program is being selectively updated, and calculations for the long-term program are being performed.

**Findings**

Creation of the unified knowledge base and the data banks as part of R&D programs in PJSC Transneft and Pipeline Transport Institute LLC is of high scientific and practical importance to the further development of PTOPP system with regard to up-to-date requirements for ensuring and improving its strength, operation life, reliability, damage tolerance, and safety. This knowledge base and the data banks shall:

- update scientific and methodological results achieved both in the industry itself and in related sectors
- facilitate the transition of the pipeline transport to a new level of compliance with the industry’s future-oriented demands, methods and criteria using up-to-date fundamental and applied theories, constitutive equations and their parameters
- contribute to reducing social, economic, environmental and technogenic risks in the area of national security and PTOPP system safety and protection.

Scientifically based selection of the hierarchy, structure, key indicators, concepts, definitions in the knowledge base and the data banks at the stage of their creation and implementation is an important initial step in the activities of the relevant business units of PJSC Transneft and Pipeline Transport Institute LLC.

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Competing interests

The authors declare that there is no competing interest regarding the publication of this paper.

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