The cross-disciplinary approach to analysis and forecast of operational damage tolerance of the oil pipeline system – part 2

by Sergei S. Sherbakov*

1 State Committee on Science and Technology of the Republic of Belarus, Minsk, Belarus
2 Belarusian State University, Minsk, Belarus

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ABSTRACT

The paper presents the cross-disciplinary approach to the analysis of the oil pipeline system based on the methodologies of tribo-fatigue and mechano-thermodynamics. The pipeline section is analyzed as a complex system pipe-soil-liquid subject to the set of mechanical, thermal and friction loads. It is shown that these loads are mainly repeatedly-alternated, and the pipe metal works in the multi-cycle fatigue conditions. The procedure of resonance accelerated fatigue tests is proposed, and their results are presented. Also, the unorthodox method of integrated wear-fatigue tests of the pipeline steel was proposed with the model of simultaneous pressure and wall friction actions. The presented field test results of pipes subject to the long-term operation showed that their fracture may occur not only in the near-weld zone, but also in the vicinity of internal corrosion damages. New models of three-dimensional stress-strain state and volumetric damage tolerance for the system pipe-soil-liquid flow were developed. These models were applied with regard to the pipe internal corrosion damages, defined using the inline inspection technique. A new efficient method to describe static and cyclic elastic-plastic fracture of the pipe steel with crack using the transverse strain is proposed and tested. Results of the computer-simulated propagation of the crack-like damage are based upon the model of deformed solid with dangerous volume. The new model is proposed for risk and safety assessment with regard to the ultrasonic inspection data. The algorithm of the ‘oil line pipe’ problem solution is presented for drafting a short-term plan of particular R&D actions.

Key words: oil pipeline, tribo-fatigue, mechano-thermodynamics, damage, stress-strain state, safety, mechanical fatigue, field tests, crack resistance, management.

INTRODUCTION

Cracking resistance of pipe steel

Numerous and various models for assessing the impact of growing single cracks on the bearing capacity and life time of oil line pipes are well known and widely used (as shown by the algorithm in Fig. 1).

When determining the cracking resistance of pipe steels, the criteria of linear fracture mechanics (LFM) based on stress intensity factors (SIF) are usually used. At that, the LFM formulae are considered to be valid in the plain strain state, which is not always observed due to the high plastic properties of the pipe material.

At the same time, several papers [1–6 et al.] show that the transverse strain can serve as an effective tool for describing both static and cyclic elastic-plastic fracture of solids with cracks (Fig. 1). The value of the residual transverse strain (necking) \( \psi = 1.5 % \) is used as a criterion for the transition from plain strain to plain stress. Authors [7–10] propose to account for the ductility of the material by adjusting the correction function \( \psi \) in the formula for SIF calculation as follows: as an argument for this function, the ratio of the crack length \( L \) to the characteristic size \( B \) of the specimen shall be replaced by the ratio of the actual (with regard to...
the plastic strain) area $F_1$ of the specimen’s dangerous cross-section corresponding to the crack length $L$ to the nominal area $F_0$ of this cross-section, i.e. $Y = (F_1 / F_0)$. Then,

$$\hat{K} = K^f = f(\sigma, L)Y(F_1 / F_0).$$  \hspace{1cm} (1)

Thus, SIF value at off-centered tension of compact specimen is calculated using the formula:

$$K_{max}^f = \frac{P_{max}}{t_0} \omega^2 \sigma \phi, \omega = \frac{F_1}{F_0}; t_0$$  \hspace{1cm} (2)

Where:

- $P_{max}$ means the maximum load of the cycle
- $\omega$ means the local damage rate to the specimen with crack
- $\omega = F_1 / F_0$; $t_0$
- $B$ mean the dimensions of the dangerous cross-section of the specimen (Fig. 1)

$$Y(\omega_x)$$ means the correction function determined as follows:

$$Y(\omega_x) = 29.6 - 185.5(\omega_x) + 557.7(\omega_x)^2 - 1017(\omega_x)^3 + 638.9(\omega_x)^4.$$  \hspace{1cm} (3)

The correction function (3) takes into account not only the geometry of the specimen and the loading configuration, but also the integral value of plastic strain in the dangerous cross-section, and formula (2) contains $\omega = F_1 / F_0$ - the local damage rate to the specimen with crack. This rate has not only the geometrical sense, but the physical content as well: it unambiguously determines the damage tolerance of an item only the geometrical sense, but also the integral value of plastic strain in the dangerous cross-section, and formula (2) contains $\omega = F_1 / F_0$ - the local damage rate to the specimen with crack. This rate has not only the geometrical sense, but the physical content as well: it unambiguously determines the damage tolerance of an item.

In order to implement this approach, it is necessary to measure the specimen necking / barreling after completion of the test, as shown in Fig. 1.

Let us give as an example the results of the evaluation of the pipe steel cracking resistance.

To study characteristics of the fracture resistance of the pipe material considering the anisotropy, compact tension specimens (Fig. 1) with notch and crack orientation along the pipe axis and in the circumferential direction were machined (Fig.2). Similarly, the samples to assess the cracking resistance of the weld metal were machined from pipes.

Using the test data, the SIF value is calculated from formula (2) and a traditional kinetic diagram of fatigue fracture (KDF) is plotted – the fatigue crack growth rate $\gamma = dl/dn = dI/dn$ versus the maximum stress intensity factor $K_{max}$ or its swing per cycle $\Delta K = K_{max} - K_{min}$. The diagram is plotted in double logarithmic coordinates $\log \gamma - \log \Delta K$ (Fig. 3).

To account for the pipe steel ductility effect on the cracking resistance characteristics, a diagram of cyclic elastic-plastic fracture (CEPF) diagram is plotted in the coordinates: SIF $K$ versus absolute $\Phi$ or relative $\Psi$-necking.

Fig. 3 shows the experimental KDFF of the compact tension specimen (with crack orientation in the pipe circumference) after long-term operation for 35–45 years, and Fig. 4 – CEPF D-diagram for the test of an axial specimen machined from the pipe in as-received condition. Stress and strain characteristics for cyclic cracking resistance of the pipe material prior to and after operation obtained using the axially-machined specimens are shown in the Table 1. One can see the significant decrease of the threshold SIF value $K_{th}$ (by 22%) in the pipe material after long-term operation.

Other SIF parameters ($K_{th}, K_{th}$) decrease less (up to 7%). And for such parameters as the ultimate necking $\Phi$, and maximum barreling $\Psi$, of the specimen, the values of the pipe material characteristics in as-received condition are 30–46% higher than similar characteristics after operation.

It is also found that the characteristics of pipe steel cracking resistance in the circumferential direction are approximately 14% higher than those in the axial direction.

A brief conclusion here is that the study of cracking resistance (using both linear and nonlinear fracture mechanics approaches) is very informative and useful for the analysis and prediction of pipe damage processes at the stage of local cracking. And considering the above, it is clear that the useful operation lifetime or resource $R$ of the pipe should be treated as consisting of two stages: stage 1 – multiple scattered damages and stage 2 – propagation of local cracks ($R = R_1 + R_2$); the latter is also called the damage tolerance of the item with a crack. Surely, all this is provided in the OLP algorithm (see Fig. 15).

An interpretation of the obtained cracking resistance parameters shall be proposed here. Since the thickness of the tested specimen is equal to the wall thickness of the pipe, its lateral surfaces retain all operational damages, and thus a change of the threshold SIF value ($K_{th}$) in the process of pipeline operation that characterizes the start of initial local crack propagation shows its high sensitivity (22% change) as the evaluation parameter for transition conditions from the stage of multiple damages to the stage of damage tolerance of the specimen with crack. Further in the test process, the crack propagates across the thickness of the specimen (which corresponds to the thickness of the pipe wall), i.e., in fact, it propagates through the base metal, where there are no wear-fatigue surface damages. And it turned out that the stress characteristics of the ultimate state (cyclic $K_{th}$ and quasi-static $K_{th}$ fracture toughness) vary only slightly (less than 7%), because they characterize, basically, the aging processes of the pipe steel. Thus, the stress parameters of cracking resistance are practically the coefficients of its strain aging, determined by the change in the bearing capacity of the pipe steel. As can be seen, the aging of the pipe material would not be as significant as the wear-fatigue damage.
However, integral ultimate plastic strains ($\phi_1$ and $\phi_2$) are, on the contrary, very sensitive characteristics of aging process (30–40%). All this seems to mean that a process of the base metal embrittlement occurs during the oil line pipe operation – similar to the process in fatigue testing. A common reason for this is the repeatedly-alternated pipe loading.

In this regard, the relevant comparative studies of aging and wear-fatigue damages seem to be very important for us today. Note here that impact toughness tests of smooth specimens (without notch) with a retained or removed surface layer of the pipe can significantly clarify the above considerations. Standard impact tests of notched specimens could probably be interpreted as it was done above for notched specimens tested for cracking resistance.

Computer simulation of the crack-like damage propagation under conditions of linear-elastic behavior of the material can be carried out using the model of deformable solid with dangerous volume [12–17] and the software package for finite element simulation, for example, ANSYS, ABAQUS, etc. For doing this, the geometric dimensions of the specimen shall be given, as well as the Young’s modulus $E$, Poisson’s ratio $\mu$ characterizing the properties of the test material, and the load $P$. Then the calculation method shall be selected for equivalent stress $\sigma$, in each elementary volume of the specimen.
The algorithm of iterative modeling of crack-like damage propagation is based on a preliminary calculation of the stress-strain state in the specimen for every (\(i^{th}\)) final element, which is considered as an elementary volume, and for which the values of average stresses and strains are available. These values are used to calculate the local damage for each finite element of model, as the ratio of applied and ultimate stresses in accordance with formula (5) from Part 1. Then in accordance with formula (6) from Part 1, an array of finite elements constituting a dangerous volume is formed, and its value is calculated using the formula (7) from Part 1.

The propagation of crack-like damage is simulated by the removal of this array from the finite element model at the current time step. In the next step, a sequential calculation of the stress-strain state, damage state and dangerous volumes is performed for a modified finite element model (with an increased damage length).

The calculation shall be terminated when the predetermined number of iterations is attained or when the dangerous volume value sharply increases compared to the previous iteration, which can be considered as the (instantaneous) state of the specimen rupture. In the two-dimensional formulation of the problem, the dangerous volume \(W\) takes the form of the dangerous area \(S\).

An example of computer modeling of crack propagation in a compact tensile specimen was performed using the following initial data: specimen dimensions \(B = 0.05\) m, \(H = 0.06\) m, \(R = 0.0625\) m; load \(P = 20000\) N; Young’s modulus \(E = 2.10^5\) MPa; Poisson’s ratio \(\mu = 0.3\). The ultimate value of equivalent stress for the material of the studied model is assumed as \(\sigma_{\text{us}} = 600\) MPa (in terms of stress intensity). The calculation results are shown in Fig. 5.

As one can see from Fig 5a, the load growth characterized by \(K\), value stipulates the relevant increment of the crack length \(\Delta L\), herewith two critical points appear (\(A_i\) and \(B_i\)), which separate three periods (\(I_1, II_2, III_1\)) of the crack propagation. Each period is characterized by a specific crack growth velocity (\(v_{\text{IV}}, v_{\text{III}}, v_{\text{II}}, v_{\text{I}}\)).

If during the crack propagation we observe the increment in its area \(\Delta S\) (Fig. 5b), then three other critical points \(A_{21}, A_{22}, A_{23}\) appear between similar points (\(A_i\) and \(B_i\)), which separate four periods \(I_{21}, I_{22}, I_{23}, I_{24}\), and each of them is characterized by certain crack growth velocity (\(v_{21}, v_{22}, v_{23}, v_{24}\)).

Comparison of Fig. 5a and Fig. 5b convincingly shows that the analysis of cracking resistance using the \(\Delta S\) parameter is much more informative than that using the \(\Delta L\) parameter and enables us to establish the jump-like growth of a crack in the period II, and also to calculate the parameters describing (characterizing) it. This is due to the fact that the value \(\Delta S\) is practically a physical parameter, whereas the parameter \(\Delta L\) is purely geometric.

Further, using the parameter \(\Delta S\), one can calculate dangerous volumes, the growth of which leads to the exhaustion of the bearing capacity of the pipe.

A brief conclusion here is that it is important to conduct the study of the pipe material cracking resistance using the elastic-plastic approach.

### Risk and safety assessment

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value for the specimen</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>prior to operation</td>
</tr>
<tr>
<td>Stress characteristics</td>
<td></td>
</tr>
<tr>
<td>Threshold value of stress intensity factor (K_{\text{sch}}), MPa(\sqrt{m})</td>
<td>7.7</td>
</tr>
<tr>
<td>Critical SIF (cyclic fracture toughness) (K_{\text{F}}), MPa(\sqrt{m})</td>
<td>(67.83-70.88)</td>
</tr>
<tr>
<td>Quasi-static fracture toughness (K_{\text{QF}}), MPa(\sqrt{m})</td>
<td>(86.89-97.19)</td>
</tr>
<tr>
<td>Strain characteristics</td>
<td></td>
</tr>
<tr>
<td>Critical crack length (L_c), mm</td>
<td>(21.00-23.00)</td>
</tr>
<tr>
<td>Ultimate necking of the specimen (\Phi_c), mm</td>
<td>(1.2-1.62)</td>
</tr>
<tr>
<td>Maximum barreling (\Phi_d), mm</td>
<td>(1.11-1.17)</td>
</tr>
</tbody>
</table>

**Table 1. Summarized stress and strain characteristics of cyclic cracking resistance of the pipe material prior to and after operation.**
An original method to assess the risk of facilities’ operation was developed in Scientific and Production Group TRIBOFATIGUE Ltd which has not yet been applied to analyze the oil line pipe states but seems to be promising for this purpose. The essence of the method is explained by a special example of operational risk assessment for girth welded joints of an oil line pipe using the criterion of dynamic strength. At the same time, the risk is associated with the pipe quality assessment according to this criterion. The work was performed at “Gomeltransneft Druzhba” JSC in cooperation with Scientific and Production Group TRIBOFATIGUE Ltd.

We will search for the relationship between the impact toughness $K_C$, the response function $Y$ of the ultrasonic test (UT) inspection and the risk of welded joints operation using the algorithm presented in Fig. 6.

The statistical quality indicator $\Pi(x)$ (Fig. 7) is the probability $P(x \geq x^*)$ that the $x$ values of the studied characteristic, for example, $x = K_C$, exceed its normative value $x^*$, determined by the relevant regulatory document (standard, specifications, etc.) [18-20].

$$\Pi(x) = \int_{x^*}^{\infty} p(x)dx = \frac{1}{\sqrt{2\pi \sigma_x}} \int_{x^*}^{\infty} \exp \left[ -\frac{1}{2} \left( \frac{x-x^*}{\sigma_x} \right)^2 \right] dx.$$

(4)

where $p(x)$ means the distribution density of the studied property characteristic, for example, $x = K_C$.

<table>
<thead>
<tr>
<th>Category</th>
<th>$\Pi(x)$, no less than</th>
<th>$D(x)$, no more than</th>
<th>$[p(x)]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Highest</td>
<td>0.995</td>
<td>0.005</td>
<td>0.0050</td>
</tr>
<tr>
<td>First</td>
<td>0.990</td>
<td>0.010</td>
<td>0.0101</td>
</tr>
<tr>
<td>Second</td>
<td>0.950</td>
<td>0.050</td>
<td>0.0526</td>
</tr>
</tbody>
</table>

Table 2. Normative values for statistical indicators of quality, its degradation and risk per STB 1234-2000.

The statistical quality degradation indicator $D(x)$ for the same characteristic $x = K_C$ (Fig. 7) is the probability $P(x < x^*)$ that the $x$ values of the studied characteristic fall outside its lower limit $x^*$, stipulated by the relevant regulatory document:

$$D(x) = P(x \leq x^*) = \int_{-\infty}^{x^*} p(x)dx = 1 - \Pi(x).$$

(5)

Depending on the facility’s economic and other criticality, which is established on the basis of technical and economic estimations, three categories of its quality are introduced in accordance with STB 1234-2000, (Table 2). Each category is determined by the corresponding normative value of interrelated statistical quality indicator, its degradation and risk.

According to traditional concepts, the risk means the expectation of quality degradation (at manufacturer and / or consumer). Risk characteristic $\rho(x)$ is the ratio of individual (partial) indicators ($D(x)$ and $\Pi(x)$) for this characteristic $x$:

$$\rho(x) = \frac{D(x)}{\Pi(x)}.$$

(6)

Practically, the risk is analyzed in the interval

$$0 \leq \rho(x) \leq 1.$$

(7)

The lower risk value $\rho(x) = 0$ corresponds to the case, when the quality degradation indicator $D(x) = 0$; its upper value $\rho(x) = 1$ in the formula (7) is limited by the condition that the indicator of quality and its degradation are equal, i.e.

$$\Pi(x) = D(x) = 0.5.$$

According to (6), the lower is the risk indicator $[\rho(x) \Rightarrow 0]$, the higher is the material quality, and vice versa, the risk indicator growth $[\rho(x) \rightarrow 1]$ means the relevant quality degradation. These regularities are reflected in formulae,
Figure 6. Algorithm to assess the relationships between $KC$, $Y$, $\rho$.

By which the risk can be calculated using only the quality indicator

$$\rho(x) = \frac{1}{\Pi(x)} - 1,$$

or using only the quality degradation indicator

$$\rho(x) = \frac{1}{1 - D(x)} - 1,$$

which is very convenient in practice.

The dependence of $\Pi(x)$ and $D(x)$ on $\rho(x)$ agreed in the formula (5) is called the operational risk characteristic. In Fig. 8, the vertical dotted line shows the allowable risk value, and the horizontal dotted lines show the corresponding values of indicators $\Pi(x)$ and $D(x)$.

In the context of the problem to assess the impact toughness of welded joints, let’s take $x = KC$ and $\rho(x) = \rho(KC)$, where $KC$ – impact toughness of specimens with welded joint. The studies are based on algorithm (1) and formulae (4), (5) and (6). Then using the results of statistical impact toughness tests, it becomes possible to establish the correlation of the operational risk with the inspection data, for example, ultrasonic and/or magnetic. This solves the practically important task to control the quality of welded joints in order to minimize or even to prevent dangerous operational damages to pipes within a certain period of time. The experimental risk indicators data are summarized in Table 3.

Fig. 9 and Table 3 show the analysis of experimental data based on the results of statistical impact toughness tests using the specimens machined from girth welds of 720-mm pipes. According to figure 9, the risk of operation increases with a decrease in the values of impact toughness; the critical state $\rho(x = 1.0)$ is attained when $KC \sim 10$ J/cm$^2$. 
Then the problem is formulated to find correlation between impact toughness $KC$ and any parameter of the UT inspection.

During UT inspection, the response functions $Y$ were obtained (on y-axis) along the pipe wall thickness (on x-axis). The example is shown in Fig. 10 as four realizations of the response function $Y$ with digitized coordinate axes. As seen, each realization is substantially different in $Y$ magnitude: its variations are 3–5-fold and even more. Therefore, it is necessary to consider response functions as random processes of UT inspection. Then, it is not difficult to calculate their average values and root-mean-square deviation for welded joints and the base metal. The quantitative parameters are given in Table 4; it is assumed that the values of $Y$ are normally distributed.

The following conclusions can be drawn from Table 4. The maximum values of the UT response function for the welded joint and the base metal differ significantly (~32%). This indicates the existence of non-continuities (flaws) of the metal in the weld seam. The same can be said about the other parameters: root-mean-square deviation is ~10%, dispersion is ~32%.

Table 3. Assessment of statistical indicators of quality, its degradation and risk based on experimental data.

<table>
<thead>
<tr>
<th>Specimen type</th>
<th>$\Pi(KC)$</th>
<th>$D(KC)$</th>
<th>$\rho(KC)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weld joint without notch</td>
<td>1</td>
<td>$1.58\times10^{-10}$</td>
<td>$1.58\times10^{-10}$</td>
</tr>
<tr>
<td></td>
<td>0.3</td>
<td>0.1053</td>
<td>0.8947</td>
</tr>
<tr>
<td>Weld joint with notch, mm</td>
<td>0.5</td>
<td>0.2206</td>
<td>0.7794</td>
</tr>
<tr>
<td></td>
<td>0.7</td>
<td>0.5391</td>
<td>0.4609</td>
</tr>
<tr>
<td></td>
<td>1.0</td>
<td>0.4673</td>
<td>0.5327</td>
</tr>
</tbody>
</table>

Figure 7. To the determination of material quality statistical indicators using the mechanical properties.

Figure 8. Operational risk characteristic in terms of the material quality.

The relationships between $KC$, $\rho$ and $Y$ plotted using the experimental data are shown in Figs. 11 and 12. As can be seen, the relationship between the impact toughness and the parameters of UT-inspection in double logarithmic coordinates is linear (Fig. 11). The trend is as follows: a decrease in $Y$ means a corresponding increase in $KC$. On the other hand, it was found that the risk also becomes higher with increase in the value of UT response parameters (see Fig.
This relationship is nonlinear. These results convincingly illustrate the effectiveness and practical significance of the facilities’ operation risk studies using certain parameters of non-destructive testing and material strength.

The risk indicator turns out to be an integrated characteristic that simultaneously considers (and describes in a single number) both the danger and the safety (reliability) of the welded joints operation. Based on the results of statistical tests, an operational risk profile is plotted as an overall rating of the welded joint quality and its strength criterion.

The established trends enable us to formulate effective recommendations on possible risk mitigation or prevention for the welded joints operation. In general, this is achieved by solving the relevant multi-criteria optimization problem.

<table>
<thead>
<tr>
<th>Specimen type</th>
<th>$Y$, min–max</th>
<th>$\bar{Y}$</th>
<th>$\bar{S}_Y$</th>
<th>$\bar{D}_Y$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weld joint without notch</td>
<td>0.0126–0.9930</td>
<td>0.1672</td>
<td>0.1080</td>
<td>0.0130</td>
</tr>
<tr>
<td>Base metal without notch</td>
<td>0.0126–0.6787</td>
<td>0.1508</td>
<td>0.0912</td>
<td>0.0089</td>
</tr>
</tbody>
</table>

*Table 4. Response function parameters.*

![Figure 9. Risk indicator versus the impact toughness.](image)

![Figure 10. Fragment of UT-inspection response function ($Y$) along the pipe wall thickness ($h$) ($Y$ scale range is increased).](image)

![Figure 11. Regression relationship of mean values $\bar{Y}$ and $KC$.](image)

![Figure 12. Risk of welded joints operation versus UT-inspection parameter $\bar{Y}$.](image)

12)
with the unconditional requirement to minimize the total costs $C_{ct}$ of the pipeline operation. The solution of such a problem is beyond the scope of this work.

The above results are related to the analysis of the relationship between the quality and the risk of the facility operation (welded joint of pipes) using one criterion of performance (mechanical properties) – the impact toughness. With regard to a large number of characteristics of the pipes performance, we have in formulae (4)–(6)

$$\left. \begin{aligned} &Y \rightarrow \min \\ &KC \rightarrow \max \\ &\rho \rightarrow \min \\ &C_{ct} \rightarrow \min \end{aligned} \right\}$$

then, for example in the partial case, considering only six main characteristics of mechanical properties, we can propose a number of single, paired and integrated pipe quality indicators according to these properties (Fig. 13). Surely, among the total number of $x_{i}$, there may exist such integral characteristics as resistance to mechanical and corrosion-mechanical fatigue, wear resistance in erosion or corrosion-erosion conditions, strength during tests of pipes loaded by the internal pressure (static and cyclic), etc. Then, the calculations according to formulae (4)–(6) consider the fact that $x = x_{i}$. Further, the new algorithm is formed:

$$\frac{D(x_{i})}{\Pi(x_{i})} = \frac{P(t)}{\lambda S_{p}} = k_{p}P(t);$$  \hspace{1cm} (10)

$$1 - \frac{P(t)}{\lambda S_{p}} = 1 - \frac{Q(t)}{\lambda S_{p}}.$$  \hspace{1cm} (11)

where $P(t)$ and $Q(t)$ mean probabilities of pipe failure and failure-free operation, $\lambda$ means the transient function, $k_{p}$ means the scale factor and $S_{p} = 1 - \rho$ means the safety indicator associated with the risk parameter $P$. Realization of algorithms (10) and (11), although difficult, is possible.

Let’s emphasize: according to algorithms (10) and (11), the integral indicators of the pipe operational reliability ($P(t)$, $Q(t)$) are assessed, which are simultaneously the integral characteristics of its quality according to the accepted criteria. The similar problem is formulated and set in the algorithm shown in Fig. 15, regarding oil line pipes (oil pipeline system).

A brief conclusion here is that the further progress of the stated approach may be seen in two directions. First, if the individual characteristics of the properties ($x_{i}$) are defined as relative parameters ($x_{i}/x_{m}$, where $x_{m}$ means the corresponding normative value of each characteristic), then all the values in the studied parameters are dimensionless, which has an important practical consequence. Second, in this case, the number $i$ of the characteristic $x_{i}$ may include not only parameters characterizing the mechanical and service properties of the pipe, its metal, welded joints etc., but also the parameters describing, for example, the geometry of the pipes, deviations (from standard values) of its size, etc. It is easy to understand the practical importance of such analysis for the integral quality assessment of pipeline systems closely connected with a possible variety of operating conditions.

**Figure 14.** Variations in operating pressure, oil pumping volumes and operational reliability of the linear part of the “Druzhba” oil pipeline.
Using this figure, the global multi-criteria optimization problem can be solved:

\[ t_z \Rightarrow \max, \ X \Rightarrow \min, \ \prod(X) \Rightarrow \max, \ \rho \Rightarrow \min, \ S_p \Rightarrow \max, \ \mathcal{C}_2(t_z) \Rightarrow \min, \ P_{\gamma} \Rightarrow \max \]

**Figure 15. Possible OLP algorithm processing flowchart (Fig. 15).**

**Monitoring and control**

The analysis of these complex problems is beyond the scope of this paper. And therefore, we will give here only an example of the effectiveness of work in this area.

By 1996, the situation in the Republican Unitary Enterprise Gomeltransneft Druzhba happened to be difficult: by the end of the depreciation period, the operational failures of the line sections (LS) of the pipeline were and remained systematic, even despite the decrease in pressure (after 1988) (Fig. 14). But a little earlier, in anticipation of the end of the depreciation period, Gomeltransneft Druzhba in cooperation with Scientific and Production Group TRIBOFATIGUE Ltd. have started the intense work on the search, development and implementation of effective measures to maintain and partially restore the LS reliability (operation capability).

These works were successful: in the next 12 years, only
3 failures of LS were recorded (see Fig. 14), but they were caused by violating the rules of construction and installation works in the vicinity of the pipeline. Especially important: during this critical period, the oil pumping pressure increased significantly and attained the value of 4.5 MPa, which is significantly higher than the design pressure (4.2 MPa).

Result: the throughput capacity of the pipeline has attained 50 mln. tons per year (see Fig. 14). The BELNEFTEKHIM Concern has officially confirmed the high economic effect. Concern has officially confirmed the high economic effect.

In this regard, it seems reasonable to accept the proposed algorithm (see Fig. 15) of the oil line pipe problem solution and its certain particular definition (Fig. 15) as a basis for the development of a short-term (for example, 5-year) plan of specific R&D activities.

As already noted, the main purpose of the algorithm presented in Fig. 15 is to significantly improve the accuracy of assessment and prediction of mechanical states of oil pipeline systems in the process of their operation in various conditions on the basis of the achievements of modern applied science. This includes: stress-strain state, damage state, risk / safety state, ultimate state and, integrally, the quality state. This combination ensures optimal resource management of oil pipeline systems and of their individual sections.

In conclusion, we should say that the algorithm presented in Fig. 15 is not complete, of course. Moreover, this is only the first proposal that requires extensive and careful discussion by experts and scientists. But being properly finalized (as a result of the corresponding R&D package implementation), it can and shall, in our opinion, become universally recognized and probably standard tool for the oil transport industry, because it covers the well-founded and outlined its most important cluster.

Competing interests

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

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