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ABSTRACT

of the dissertation for the degree of Doctor of Philosophy

INVESTIGATION OF THE RESIDUAL SERVICE LIFE OF OIL AND GAS PIPELINES CONSIDERING EXTERNAL AND INTERNAL IMPACTS

Speciality:	3354.01 - Construction and operation of oil and gas pipelines, bases, and storage facilities
Field of science:	Technical Sciences
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The dissertation was performed at the "Research of Hydraulic Structures" Laboratory of SOCAR's "Oil and Gas Scientific Research Project" Institute.

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GENERAL CHARACTERISTICS OF THE RESEARCH

Relevance and Degree of Development of the Topic. During the development of oil and gas fields, the safe and reliable transportation of produced hydrocarbons is one of the key technological challenges. In this regard, oil and gas pipelines are complex structural systems exposed to the combined effects of various external and internal factors. Particularly, during the design and operation of subsea pipelines, the characteristics of the marine environment, water and soil temperatures, hydrostatic pressure, seabed topography, flow effects, and the physicochemical properties of the transported product must be taken into account.

The reliable operational capability of pipelines is determined not only by their initial strength characteristics but also by changes in their stress-strain state during the service period, material fatigue, corrosion processes, crack propagation, and the formation of various types of defects. External hydrostatic effects, internal pressure, temperature variations, and dynamic loads lead to the occurrence of additional stresses in the pipe wall, which over time result in a reduction of the pipeline's strength reserve and remaining service life.

In modern times, various-purpose oil and gas pipelines located both onshore and in the Azerbaijani sector of the Caspian Sea have been in operation for extended periods. When assessing the technical condition of these pipelines, it is important not only to identify existing defects but also to determine the development dynamics of these defects, changes in the stress state, and the future reliable operating period of the structures. For this purpose, the assessment of the remaining service life of pipelines based on technical and technological diagnostic data is of particular importance.

It should be noted that the problems associated with determining the remaining service life of oil and gas pipelines, taking into account external and internal effects, phase transformations, structural changes, and dynamic loads, have not yet been fully resolved. In existing calculation methods, the complex stress states occurring in pipelines and the interaction of various influencing factors are not always sufficiently considered.

The development of scientifically substantiated calculation methods that consider external and internal impacts is of significant scientific and practical importance for ensuring the strength and stability of pipelines and for more accurately assessing their remaining service life.

Among the studies devoted to the strength and stability of offshore oil and gas pipelines, the works of A.Kh. Mirzajanzade, M.T. Abbasov, A.B. Suleymanov, S.A. Orudzhov, I.R. Guliyev, Y.A. Safarov and others in Azerbaijan; as well as P.P. Borodavkin, V.I. Chernik, E.M. Yasin, S.I. Levin, M.A. Kamyshev, V.V. Aleshin, Y.I. Goryanov, G.G. Vasilyev, V.G. Orlov, B.L. Krivoshein, N.I. Tugunov, S.Y. Kushnir, V.A. Kudryavtsev, I.A. Ivanov, A.M. Shammazov, F.K. Khabibullin, G.G. Korovkov, A.G. Bumerov, M.A. Guseinzade, P.G. Riselev, I.A. Kutukov, L.S. Leybenzon, M.E. Lurie, I.A. Charny, V.A. Yufin, T.I. Lapteva and others in the former USSR can be mentioned. Despite certain achievements obtained in this field, research in the above-mentioned areas remains relevant.

Object and Subject of the Research. The object of the research is various-purpose oil and gas pipelines installed both onshore and offshore. The subject of the research is the assessment of factors affecting the operability of pipelines and their remaining service life, taking into account external and internal influences.

Aim and Objectives of the Research. The aim of the research is to determine the remaining service life of onshore and offshore oil and gas pipelines based on the assessment of their reliability parameters, taking into account a new physical model of flow, structural changes, and dynamic loads. To achieve this aim, the following tasks were considered:

- analysis of the main requirements for oil and gas pipelines, methods for ensuring their operability, and approaches to strength and stability calculations;

- analysis of problems related to the installation technologies of subsea pipelines;[1]

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[1] Iskandarov E.Kh. Technology of Construction and Installation of Oil and Gas Pipelines. – Baku: Elm, 2022. – 416 p.

- diagnostics of oil spills in free-flowing pipelines;
- technical diagnostics of gas well flowlines;
- assessment of the remaining service life of pipelines based on diagnostic data;
- calculation of pipelines considering a new physical model and structure of flow;
- strength and stability assessment of high-pressure steel pipelines;
- substantiation of the effect of dynamic loads on the reliability and operational capability of pipelines;
- investigation of lateral buckling of subsea pipelines;
- application of a new method for diagnosing wall thickness losses in pipelines.

Research Methods. The objectives set in the research were solved through theoretical and practical approaches based on the analysis of data related to the construction, operation, and internal and external diagnostics of oil and gas pipelines. Standard laboratory equipment and testing methods, as well as computer modeling and software tools, were used in the research.

Main Provisions Submitted for Defense:

1. A method for assessing oil spills (ballast volume) into the environment under gravity-driven flow conditions in relief pipelines, taking into account the multiphase nature of the flow;

2. A method for determining the remaining service life of pipelines based on technical and technological diagnostic data;

3. The influence of the velocity-gradient field formed by the interaction of phases in multiphase flows, in contrast to single-phase flows, and the effect of dynamic loads on the structural reliability and service life of pipelines.

Scientific Novelty of the Research:

- A method has been developed for assessing oil spills (leakages) into the environment under gravity-driven flow conditions in relief pipelines, taking into account the multiphase nature of the flow;

- A method for determining the remaining service life of pipelines based on technical and technological diagnostics has been developed;
- The influence of the pressure gradient formed by phase interaction and dynamic loads on the service life of pipelines has been determined and theoretically substantiated.

Theoretical and Practical Significance of the Research. The reliability and strength assessment of multiphase pipelines, taking into account the new physical model of flow and phase interaction, is of great importance for the accurate evaluation of their remaining service life.

The proposed method for assessing oil spills and environmental impact during gravity-driven flow caused by defects in relief pipelines has practical significance.

The approaches proposed based on technical and technological diagnostic data enable more accurate determination of the remaining service life of oil and gas pipelines. The effects of dynamic loads and phase transformations on the structural strength of pipelines have been evaluated.

The proposed mathematical methods and formulas can be used in the educational process for the calculation of oil and gas pipelines, including at bachelor's and master's degree levels.

Approbation and Application of the Research. The main results of the dissertation were presented and discussed at the relevant scientific seminar of the "Neftqazelmitədqiqatlayihə" Institute and at the following scientific seminars and conferences: Republican Scientific Conference dedicated to the 100th anniversary of the birth of National Leader Heydar Aliyev on the topic "Problems and Prospects of Oil and Gas Field Exploration", Baku, 2023; XXVII Republican Scientific Conference of Doctoral Students and Young Researchers, Baku, 2024; International Conference Energy and Environmental Technologies in Engineering and Architecture (ICETEA-2024), December 19–21, Baku, 2024.

Publications. The main results of the dissertation research have been reflected in 13 scientific publications, including 5 articles without co-authors. Among them, 3 articles have been published in peer-reviewed scientific journals included in international abstracting and indexing databases. A total of 4 conference papers have been published based on the results of national and international scientific events, including 1 publication abroad.

Name of the Organization Where the Dissertation Was Carried Out. The dissertation research was carried out at the SOCAR "Neftqazelmitədqiqatlayihə" Institute.

Number of Characters and Volume of the Dissertation. The structure and volume of the dissertation were determined by the logic of the research and the sequence of solving the formulated objectives. The dissertation consists of an introduction (12,124 characters), three chapters (Chapter I – 52,894 characters, Chapter II – 55,639 characters, Chapter III – 80,984 characters), conclusions, and a list of 127 references. The total volume of the dissertation is 162 pages, comprising 216,263 characters.

CONTENTS OF THE DISSERTATION

The introduction provides the justification of the relevance of the research, defines the aim and objectives of the study, presents the scientific novelty, practical significance, and provisions submitted for defense, and briefly describes the content of the dissertation.

The first chapter of the dissertation is entitled "Analysis of Factors Affecting the Operability of Oil and Gas Pipelines and Methods of Their Diagnostics" and consists of five sections. This chapter provides a comprehensive analysis of the operational characteristics of subsea and mainline pipelines, the factors affecting their reliability, as well as modern methods for diagnostics and assessment of strength and stability.

The first section presents a detailed analysis of the main design requirements for pipelines. It discusses the selection of pipeline diameter and wall thickness, optimization according to hydraulic and mechanical loads, arrangement of fittings and connecting elements, as well as engineering requirements related to the minimum bending radius along the pipeline route. In addition, regulatory approaches and design limitations ensuring operational safety are systematized.

The second section examines the application areas of subsea marine pipelines and the specific features of their design. The influence of complex hydrological and geomorphological characteristics of marine conditions on design solutions is demonstrated, and the necessity of thermal and hydraulic calculations to ensure optimal transportation regimes is substantiated. Issues related to multiphase flow modeling, seasonal variations, and selection of operational parameters are also considered.

The third section presents the classification of defects occurring in pipelines and the criteria for selecting diagnostic methods. Defects are systematized according to their origin, structure, and location, while major failure types such as corrosion, welding defects, and mechanical damages are analyzed. In addition, generalized information is provided on the application of ultrasonic, magnetic, and other non-destructive testing methods, including their advantages and limitations.

The fourth section provides a comprehensive overview of the objectives, tasks, and sequence of technical diagnostics. The role of technical diagnostics in industrial safety, assessment of the residual service life of equipment, optimization of operational parameters, and timely detection of defects is substantiated. At the same time, the principles of considering environmental conditions and technical solutions during the selection of initial design parameters for subsea pipelines are systematized.

The fifth section presents an extensive analysis of strength and stability calculations for subsea pipelines. It includes the main theoretical approaches and calculation formulas related to determining wall thickness, calculating allowable stresses, assessing the effects of external and internal pressure, as well as evaluating pipeline behavior under bending and local stability loss conditions. In addition, safety criteria considering fatigue, impact loads, and seismic effects are summarized.

As a result, the first chapter systematically analyzes the main requirements for the design and operation of subsea pipelines, methods for defect detection and assessment, as well as fundamental principles of strength and stability calculations. Based on the performed generalizations, a methodological and scientific basis has been established for ensuring the safe and reliable operation of subsea pipelines.

The second chapter of the dissertation is entitled "Improvement of Pipeline Operability and Assessment of Residual Resources Based on Technical and Technological Diagnostics" and consists of seven sections. The main objective of this chapter is to investigate modern approaches applied for increasing the operational reliability of subsea and onshore pipelines, assessing their technical condition, and predicting their remaining service life.

The first section provides a detailed analysis of the main technological challenges arising during the installation of subsea pipelines. In particular, modern technologies used for pipeline connection operations on the seabed, including flanged connection systems, hyperbaric welding methods, and operations performed using remotely operated vehicles (ROVs – Remotely Operated Vehicles), are discussed in detail. Each of these technologies plays an important role in ensuring safety, accuracy, and reliability of operations under deep-water conditions, while their application contributes to reducing overall technical risks of the project.

Furthermore, the behavior of pipelines under external loads was analyzed in accordance with the DNVGL-ST-F101 Norwegian offshore standard. Within the framework of this standard, the Load Controlled Condition (LCC) approach was applied to model the deformation characteristics of pipelines under hydrodynamic, hydrostatic, and additional mechanical effects. The modeling process was performed using the MATLAB software environment, and simulation results were obtained for various depth conditions and loading scenarios.

n particular, the displacement behavior of the pipeline was analyzed based on calculations performed for a water depth of 300 m in the Caspian Sea. The obtained results demonstrate that hydrodynamic forces, flow velocity, and seabed topography characteristics have a direct impact on the overall deformation behavior of the pipeline. During the comparison of pipelines with different wall thicknesses, as shown in Figure 1, it was observed that an increase in wall thickness leads to higher pipeline stiffness, resulting in closer displacement curves and more stable structural behavior. This can be explained by the increase in the structural stability of the pipeline and its enhanced resistance to external effects.

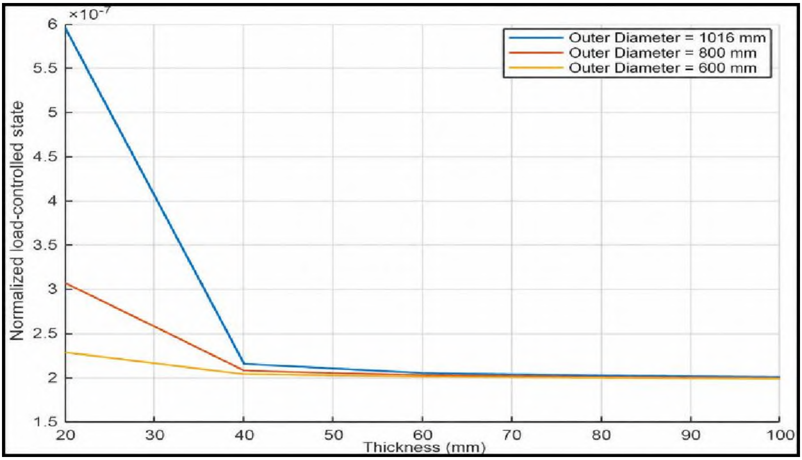


Figure 1. Displacement of pipelines with different diameters and wall thicknesses under the influence of loads at a water depth of 300 m in the Caspian Sea

The second section presents the technical diagnostic works carried out on a flowline operating under actual service conditions. The diagnostic process initially included visual inspection, during which defects such as corrosion, mechanical damage, and coating degradation on the pipeline surface were identified. Subsequently, ultrasonic thickness measurement was performed using a DM5E-type thickness gauge, and measurements were taken at various points along the pipe wall.

The obtained measurement results were compared with the requirements of the existing regulatory documents, and the operational suitability of the pipeline was assessed. The performed analysis showed that, although a reduction in wall thickness was observed in some local areas, the overall operational reliability indicators of the pipeline were found to be satisfactory. This approach provided an important scientific basis for determining the remaining service life of the pipeline and predicting its future operational period.

According to the technical diagnostics and visual inspection performed on the flowline of gas well №184 located at offshore stationary platform №10 of the "Gunashli" field operated by the "28 May" Oil and Gas Production Department, the calculations demonstrated that the actual wall thickness of the flowline (2.65 mm) is lower than the allowable thickness (3.91 mm). Therefore, the flowline was determined to be unsuitable for further operation.

The third section presents the criteria for identifying and evaluating stress concentration zones based on the contactless magnetometric diagnostics (Metal Magnetic Memory method) approach for assessing the technical condition of pipelines. The issues related to the selection of hazardous zones based on the distribution of residual magnetic fields are also considered.

The fourth section briefly and sequentially describes the operating principle and procedure of launching and receiving chambers used for in-line inspection of pipelines, including the operation of inspection tools, valves, pressure equalization processes, and related operations.

The fifth section addresses the assessment of oil spills during accidental free gravity-driven flow conditions. The total spill volume is explained in stages, and the importance of accurate modeling of hydrostatic pressure in pipelines with complex terrain profiles is demonstrated.

It is known that, in order to assess losses caused by accidental oil spills during the operation of oil pipelines and to evaluate the environmental impact, mathematical models for estimating spilled oil volumes have traditionally been based on the hydraulics of single-phase flow of liquids and gases through openings and nozzles.

Practical experience shows that in multiphase flow systems, during accidents, a certain non-displaceable ballast volume of liquid always remains in pipelines with relief profiles.

Since pipelines are equipped with automation systems, the duration of oil flow under pressure conditions after an accident generally does not exceed approximately **2 minutes**. After the pumps are stopped, the valve is closed simultaneously, resulting in the termination of the pressurized oil flow. After valve closure, the determination of the oil volume discharged under gravity-driven (pressureless) flow conditions requires special investigation.

For the assessment of oil spills, as a rule, when damage or leakage occurs in relief pipelines, two points are identified on the pipeline profile: the maximum and minimum elevation points (points A and B in Figure 2). A pressure distribution graph along this section is then constructed to represent the pressure variation. In the considered case, the location of the accident-induced leakage (opening) is assumed to be at the minimum point of the profile, i.e., point B.

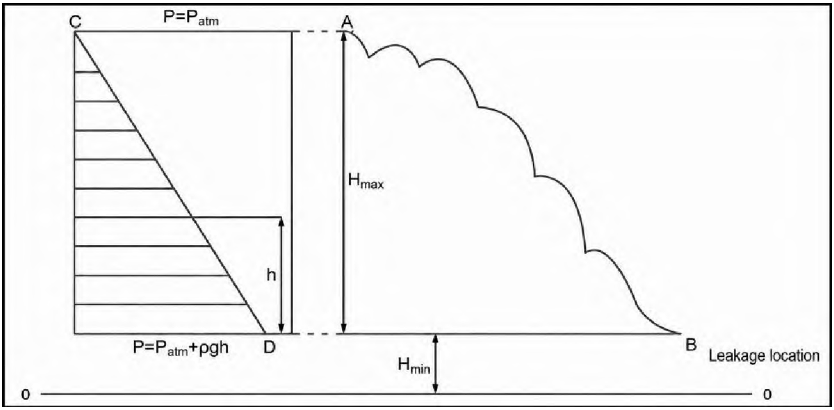


Figure 2. Hydrostatic pressure distribution along the oil pipeline section with expected leakage location (based on an incorrect assumption)

According to the existing methodology, it is assumed that the pressure in the AB section of the pipeline changes along the CD line, as shown in Figure 2, and that atmospheric pressure corresponds to the maximum point A. At this point, $P = P_{atm}$. Subsequently, the pressure increases downward along the elevation according to the law $P = P_{atm} + \rho g h$. Considering the above-mentioned pressure distribution, the velocity of oil discharge through the accidental leakage opening is determined by the following expression, which is known from hydraulics (applicable only to single-phase flows):

$$\vartheta = \sqrt{\frac{2P}{\rho}} = \sqrt{\frac{2(P_{atm}+\rho g h)}{\rho}} \tag{1}$$

Where:
h – current elevation, m;
ρ – density of oil, kq/m^3.

A detailed analysis shows that, in the AB section of the oil pipeline where an accident (leakage) has occurred, atmospheric pressure will not be established at the maximum point A of the pipeline profile, as shown in Figure 2, but rather at the minimum point B, i.e., at the leakage location. It is from this opening that the pressure increases in the downward direction as the height of the liquid column increases. In this case, the pressure varies according to the expression $P = P_{atm} + \rho g h$.
Conversely, in the upward direction from the leakage opening, for example, at an elevation of **h**, the pressure decreases by the value of $\rho g h$, corresponding to the height of the liquid column (Figure 3).

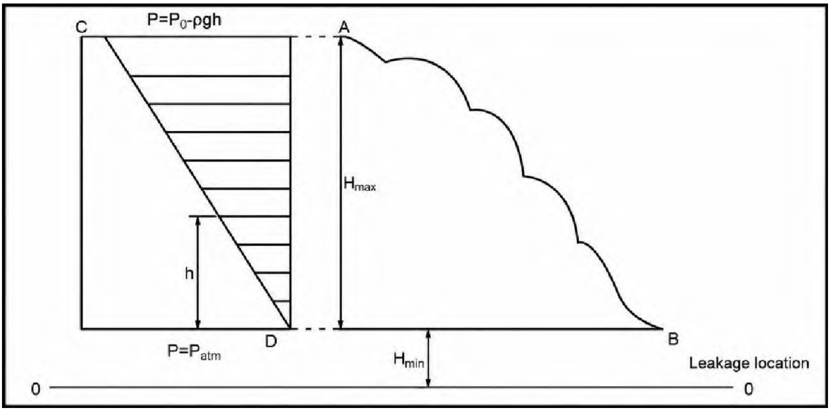


Figure 3. Hydrostatic pressure distribution at the oil leakage point (according to the actual model)

Therefore, during pressureless flow conditions, since the pressure inside the pipeline at section B is equal to atmospheric pressure, oil discharge does not occur. Free flow of oil through the accidental opening at point B will occur only if the opening is not located under water. If the leakage occurs onshore, only the section between the nearest elevation point and the opening at point B will be gradually drained. The remaining volume of oil in the pipeline will not flow out under gravity-driven conditions.

It should be noted that, unlike single-phase flows, appropriate assessment and calculation methods for multiphase flows are currently almost absent in regulatory documents and scientific literature.

In general, according to the principle of flow continuity, complete drainage of the pipeline is not possible. According to the laws of physics, the space vacated by the discharged oil must be replaced by another surrounding medium (for example, atmospheric air or oil vapor). Since pipelines with complex relief profiles may have significant elevation differences, the pressure difference between atmospheric pressure and the internal pipeline pressure can lead to the "boiling" of oil. Thus, due to pressure reduction at a certain point of the pipeline, the following condition may be satisfied:

$$P_{atm} - \rho g h = P_{b.e} \tag{2}$$

Where:

$P_{b.e}$ – vapor pressure (vapor elasticity pressure) of oil, Pa;

h – height of the liquid column measured from the leakage opening, m.

Thus, when condition (2) is satisfied, the vapors released from the oil fill the space previously occupied by the flowing oil inside the pipeline.

It should be noted that the possibility of replacing the discharged oil volume with its own vapors is determined by the vapor pressure of the oil, which depends on temperature. The variation of oil vapor pressure depending on temperature according to GOST R 51858-2002 is presented in Figure 4.

Thus, as a result of assessing oil spills under pressureless flow conditions in pipelines, it has been established that even under the most unfavorable conditions, complete drainage of the pipeline is impossible. Complete emptying of the pipeline under pressureless flow conditions during accidental oil spills can only occur when openings are formed at the extreme points of the pipeline profile.

As shown in Figure 4, the vapor pressure of oil increases with increasing temperature. This increase becomes more intensive at higher temperature values. As the temperature rises, the evaporation process of light components contained in the oil accelerates, resulting in an increase in the pressure of the vapor phase. For example, when the temperature increases from 40°C to 50°C, the vapor pressure of oil increases from 500 mmHg to 650 mmHg. This demonstrates that temperature variations have a significant effect on the physical properties of oil and on the flow processes occurring in pipelines.

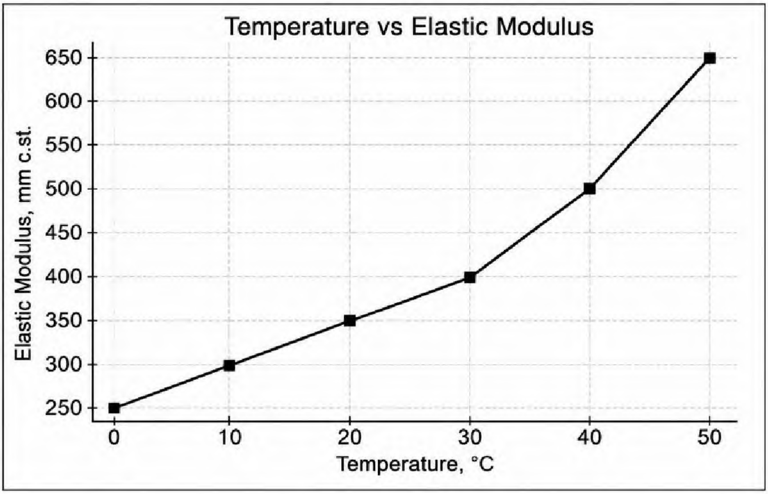


Figure 4. Dependence of oil vapor pressure on temperature

The sixth section considers the assessment of the remaining service life of pipelines based on the technical and technological diagnostic data of oil and gas field pipelines.

Considering that the clarification of reliability parameters of operating oil and gas pipelines is of particular importance from the viewpoint of safety, the necessity of using technological diagnostic data in addition to technical diagnostics performed on pipelines, as well as the importance of considering the combined effects of external and internal factors, has been demonstrated. Based on the diagnostic data, the period of reliable operational suitability of pipelines has been determined.

It has been emphasized that the assessment of the remaining service life should be carried out not only considering the important parameters such as the design wall thickness, the assumed corroded wall thickness, and the minimum allowable wall thickness, but also taking into account the overall corrosion rate. For determining the remaining wall thickness service life of the pipeline (t_{res}), the following assessment approach has been proposed:

$$t_{qal} = \frac{\delta_{min} - \delta_{kor}}{v_{kor}}, \qquad (3)$$

Burada:

$v_{kor} = \frac{\delta_{nom} - \delta_{min}}{t}$ – average corrosion rate;

$\delta_{nom,}\ \delta_{min}\ v\text{ə}\ \delta_{kor}$ – nominal, minimum, and estimated corroded wall thicknesses of the pipeline according to the design data, respectively;

t – service life of the pipeline.

The assessment of the remaining service life of oil and gas field pipelines with a diameter of D = 279 mm was considered, taking into account the operational characteristics and regulatory requirements for pipelines manufactured from Ct20 steel grade installed in accordance with GOST 8731 and operated for a period of 12 years.

Based on the diagnostic and measurement data (Table 1), the average, estimated corroded, and minimum allowable wall thicknesses, as well as the average corrosion rate of the pipeline, are respectively $\delta_{or} = 8.55\,mm$, $\delta_{kor} = 7\,mm$, $\delta_{min} = 7.52\,mm$, and $v_{cor} = 0.206\,mm/year$. Therefore, the remaining service life of the pipeline was determined to be $t_{qal} = 2.52$years.

The possibility of further operation of the pipeline was determined based on the pressure value P_0that can be withstood by the minimum wall thickness. Considering that the calculated value of this pressure is $P_0 = 9.8\,MPa$, the internal pressure in the pipeline must remain below 9.8 MPa to ensure safe operation during the predicted remaining service period (2.52 years).

The seventh section explains the new application of the Metal Magnetic Memory (MMM) method, including the assessment of stress concentration zones (SCZs) through inspection using the TSC-9M-12 device, Hp scanning, and Hp gradient analysis. The processing and interpretation of the obtained results are also presented (see Figure 5).

Table 1

Wall thicknesses determined from measurement results (mm)

Points of measurement			
I	II	III	IV
8,5	8,5	8,6	8,7
8,7	7,8	8,6	9
7,8	8,6	7,9	8,9
7,7	8,4	8,5	8,9
9,3	9,3	9,4	9,4
9,1	9	9	9
7,8	7,7	8,3	8,7

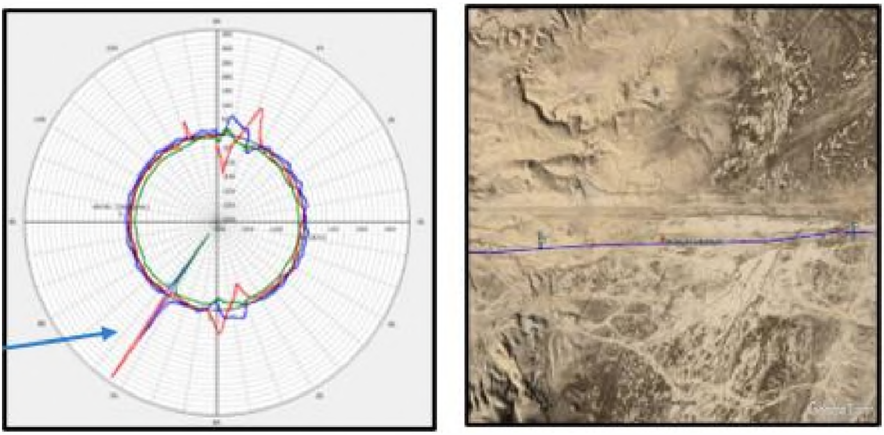


Figure 5. Anomaly magnetogram and satellite image

The approbation of the method was carried out at SOCAR's "Oil Pipelines" Department on the 530 mm diameter "Northern Export" Pipeline (NEP). The inspection results are presented in Figure 5.

The Hp parameter was recorded on the magnetogram, and the stress concentration zone was identified using satellite imagery. In the figure, GKZ 1 represents the geographical coordinates of the anomaly, while GKZ 2 reflects the delay occurring during the movement of the wheels when the position of the hand is changed.

During the magnetometric diagnostic works carried out on the underground "Northern Export" main oil pipeline, magnetic anomalies and characteristic stress accumulation zones were detected at the 14th kilometer of the pipeline.

In addition to the above, it should be noted that the soil in the investigated section consists of yellow clay, and the thickness of the soil layer above the pipeline is 1.8 m. The pipeline is insulated with an epoxy resin coating. The insulation layer at the welded joints of the pipes consists of polyethylene tape. At the section where the anomaly was detected, the welding type is manual welding, and intensive corrosion was observed around the weld seam.

Thus, the following conclusions can be drawn:

- At the section containing the SHIBK-067 anomaly, within the length of the opened excavation pit, the pipeline was inspected using a scanner device without damaging the insulation layer, defects were identified, and ultrasonic flaw detection tests were performed on these areas.

- As a result of the performed **"scan-analysis"**, a characteristic stress accumulation zone was detected through contact inspection.

- Measurements were carried out in the circumferential direction on the steel pipe, and the actual cross-sectional wall thicknesses were determined. The minimum actual wall thickness in the upper part of the pipeline is 7.76 mm, in the side part 7.55 mm, and in the lower part 7.77 mm.

- Since a Group III anomaly was identified at the excavation pit located at the 14th km of the underground section of the 530 mm diameter "Northern Export" pipeline, the corresponding pipeline sections can be considered as zones with non-uniform stress-strain states and stress concentration zones. However, the pipeline section remains suitable for operation.

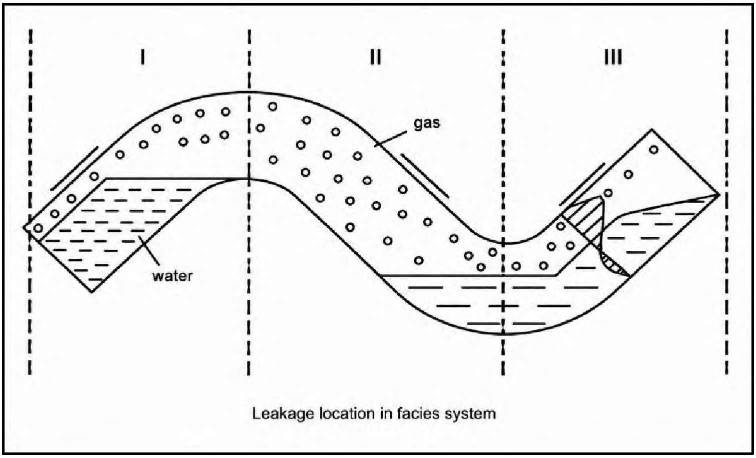
- The Metal Magnetic Memory method is indeed suitable for technical diagnostics of pipelines, and its application at other SOCAR facilities is considered appropriate.

The third chapter of the dissertation is entitled "Investigation of the Remaining Service Life of Pipelines Considering a New Physical Model of Flow, Structural Transformations, and

Transportation Technologies" and consists of seven sections.

The first section presents the formation and specification of structural flow regimes in hydraulic calculations of multiphase pipelines based on a new physical model of flow, taking into account the stability of the total pressure rather than static pressure in the cross-section of cylindrical flow, as well as the variation of the pressure gradient along the cross-section.

The mechanism of liquid transportation in gravitational multiphase flow is of significant interest due to phase interactions and varies depending on the pressure gradient across the cross-section (Figure 6).



Şəkil 6. Mechanism of liquid movement in gravity-driven flow

At the beginning of the pipeline (Section I), since the introduction of the multiphase mixture into this section is characterized by a low-stress gradient–velocity field, the transportation of dispersed liquid particles by the gas flow is not possible. As a result, separation of the mixture occurs in the pipeline, and the liquid settles at the bottom of the pipeline due to its own weight. Since the liquid cannot be transported by the gas phase, the pipeline gradually begins to fill with liquid.

Figure 6 illustrates Sections I and III with upward flow directions, Section II with downward flow direction, and the distribution of gas and liquid velocities in the free and liquid-filled cross-sections of the gas pipeline. If Section I is already filled with liquid up to the equilibrium state, Section II always operates under a "dry" regime, while Section III is in the filling stage. In Section I of the pipeline, the gas moves above the liquid layer in a stratified flow pattern. Since the cross-sectional area available for gas flow is significantly reduced due to the presence of liquid, the gas velocity increases. Although the velocity distribution of gas in the free cross-section of the pipeline is not sufficient to capture and transport liquid particles by the gas flow, the required condition for liquid transportation is satisfied in the channel filled with condensate (liquid):

After the completion of condensate accumulation in Section I, the filling of Section III begins. The liquid entering Section II together with the gas flow falls to the bottom of the pipeline and moves toward the inlet of Section III under the influence of gravitational and friction forces. Since the gas velocity in the free cross-section of Section III is low, liquid removal from this section does not occur. Therefore, liquid accumulation takes place in the lower part of the pipeline profile over a certain period of time. This process continues until the phase separation interface (PSI) reaches a horizontal position. Since part of the liquid is displaced by the gas flow, complete blockage of the pipeline cross-section by liquid does not occur at this location. The additional liquid is distributed along the length of this pipeline section.

The transportation of gas by the liquid phase (dispersed medium) occurs with an increase in the volumetric gas content of the mixture, the average volumetric flow velocity, and the pressure gradient along the cross-section of the liquid flow.

The hydraulic calculation of a pipeline transporting a multiphase mixture is performed separately for the above-mentioned conditions. Sections with a "dry" bottom, i.e., downward flow zones and horizontal sections transitioning into downward sections, are calculated as homogeneous single-phase flow according to conventional hydraulic equations.

The ascending sections of the pipeline are also calculated according to hydraulic principles for a single-phase medium, taking into account the diameter of the free channel not occupied by liquid.

The maximum value of the pressure gradient required for hydraulic calculations is determined as follows:[2]

$$(\mathrm{dP/dr})_{\max} = 6{,}16 \cdot 16 \cdot \rho_{qar} u_{qar}^2 / D \qquad (4)$$

where:

u_{qar} – mixture flow velocity, $\left(\frac{m}{san}\right)$;

$\rho_{qar,}\ \rho_m$ və ρ_q densities of the mixture, liquid, and gas, respectively, kq/m^3.

The last expression is compared with the term $(\rho_m - \rho_q)g$ to determine the flow structure, i.e., whether the flow is dispersed (emulsion-like) or stratified.

The second section considers the strength and stability calculations of technological steel pipelines operating under high pressure and temperature conditions. The effects of internal pressure (up to 10 MPa), temperature (−253…+700°C and higher), insulation weight, and other operational loads acting on pipelines, as well as wall thickness losses caused by corrosion, were investigated. Based on the calculation results, approaches for substantiating decisions regarding operation shutdown, repair periods, reduction of operating pressure, and selection of diagnostic methods were presented.

Strength and stability calculations of the pipeline were performed using the "STAAD Pro" software. A structural model of a technological pipeline with a diameter of D = 273 mm was developed, and the distribution of stress concentrations occurring in the linear section of the pipeline was demonstrated (Figure 7).

Stress concentration is one of the main criteria for determining whether a structure remains suitable for operation or becomes unsuitable. The obtained stress concentration value is calculated by converting the three principal stresses into an equivalent stress, which is then compared with the yield strength of the material to evaluate the condition of the structure.

A comparative analysis of the maximum value of the stress concentration zone (113 MPa) was performed with the allowable

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[2] Grichenko A.I., Klapchuk O.V., Kharchenko Yu.A. Hydrodynamics of Gas-Liquid Mixtures in Wells and Pipelines. – Moscow: Nedra, 1994. – 279 p

stress calculated taking into account the temperature coefficient of 15Kh1M1F grade steel, and the operational suitability of the pipeline was evaluated.

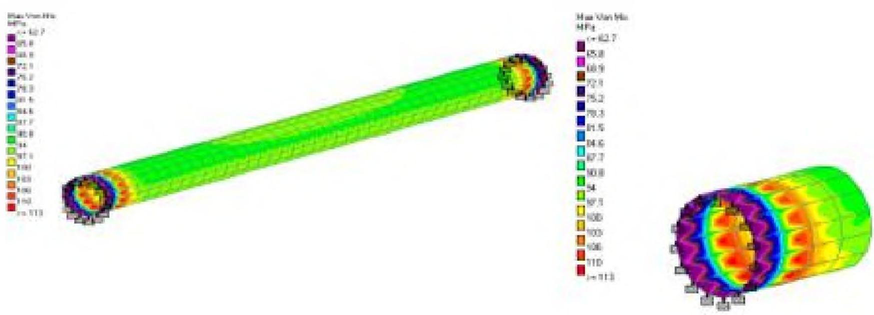


Figure 7. Stress concentration distribution in the pipeline linear section

- During the diagnostic works, the actual minimum wall thickness of the linear section of the pipeline was determined to be 24.43 mm;
- A mathematical calculation of the linear section element of the pipeline was performed, and the allowable wall thickness was determined to be 12.68 mm. By comparing the obtained value (12.68 mm) with the actual wall thickness (24.43 mm), it was concluded that the linear section element of the pipeline is suitable for operation.
- Strength and stability calculations of the pipeline were performed using the proposed software. The pipeline was analyzed considering its metal weight, operating pressure, and temperature. Based on the analysis, the maximum stress value in the stress concentration zone of the pipeline (113 MPa) was compared with the allowable stress limit (152.18 MPa) determined considering the temperature coefficient of the pipeline. Since the obtained stress value is lower than the allowable limit, the operational suitability of the pipeline was confirmed.

The third section investigates the influence of phase transformations and technological challenges arising during the operation of subsea gas pipelines, particularly the accumulation of deposits and acceleration of corrosion. The scheme of deposit accumulation inside the gas pipeline was analyzed, and the reasons for the increase in corrosion rate were identified based on long-term wall thickness measurements. The higher corrosion rate compared with the standard values was associated with the presence of deposits.

Thus, the results of the conducted research and analytical studies demonstrate that, due to the imperfection of the technologies applied for gas preparation for transportation in the investigated offshore gas-condensate fields, the gas supplied to the transportation system contains significant amounts of hydrocarbon condensate, water (both free and in equilibrium state), and mechanical impurities. During the transportation of gas through both subsea and mainline pipelines (underground and above-ground), phase transformations occur inside the pipelines due to thermobaric effects of the surrounding environment. As a result, technological problems arise due to the deposition of transported hydrocarbons, water, and mechanical impurities inside the pipeline.

The fourth section presents the substantiation of multiphase transportation technologies considering the dynamic variation of gas resources. In multiphase transportation, the application of periodic cleaning devices (pigging) and the selection of their operating frequency are justified in order to increase operational reliability due to pressure pulsations caused by flow structure transformations and condensate accumulation (Table 2).

As a result of the analysis, considering that the magnitude of dynamic loads occurring in multiphase flows depends on which phase (gas or liquid) acts as the leading carrier phase, i.e., the dispersed medium, appropriate mathematical expressions were obtained for evaluating dynamic pressures for cases where the dispersed medium is gas and liquid, respectively:

$$P_d^q = 1{,}59gD \cdot (1-\beta)\frac{\rho_m^2}{\rho_q} \tag{5}$$

$$P_d^m = 1{,}59gD \cdot (1-\beta)\rho_m \tag{6}$$

Table 2

Equilibrium condensate volume accumulated in a gas pipeline (D = 0.25 m) and pigging at different gas flow rates

Gas flow rat , min m^3/h	0,5	1,5	3,0	4,5	6,5
Volume of condensate accumulated in the pipeline , m^3	2,30	1,80	1,46	1,24	1,0
Allowable condensate filling fraction , %	35	35	25	15	0
Permissible condensate volume m^3	805	630	365	186	0
Condensate collection time, days	121	95	55	28	-
Pig launching frequency	1 time 4 months	1 time 3 months	1 time 2 months	ayda 1 months	-

Where:

D – pipe diameter, m;

β – gas holdup.

From expressions (5) and (6), the following expression can be obtained:

$$\frac{P_d^q}{P_d^m} = \frac{\rho_m}{\rho_q} \tag{7}$$

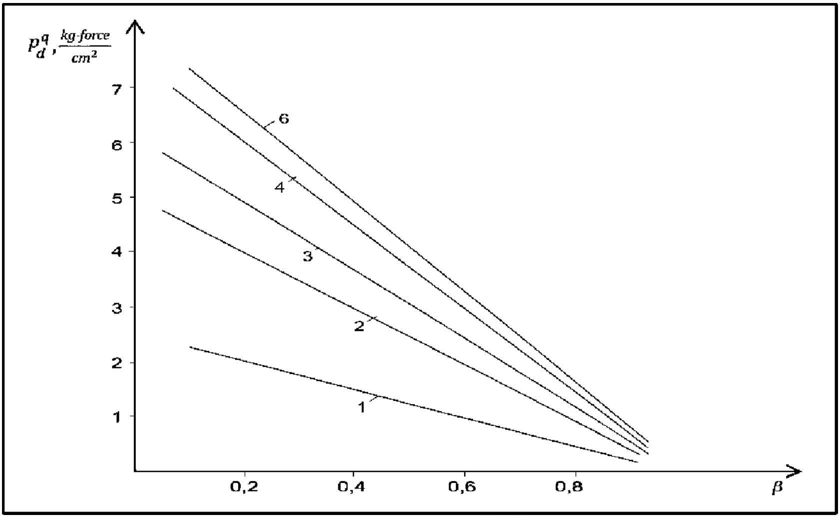
Considering that dynamic pressure is more characteristic for multiphase flows with gas as the dispersed medium, calculations were performed based on Equation (5) to determine the dependence of dynamic pressure on gas holdup and the ratio of phase densities using the following initial data:

$$D = 500mm; \rho_m = 800kq/m^3; \rho_m/\rho_q = 25; 50; 75; 90;$$
$$\beta = 0,3; 0,5; 0,7; 0,9.$$

Based on the results of these calculations, the dependencies $P_d^q = f(\beta)$ and $P_d^q = f(\rho_m/\rho_q)$ were constructed (Figures 8 and 9).

As shown in Figures 8 and 9, with an increase in gas holdup, the dynamic pressure decreases according to a linear relationship. With an increase in the ratio of phase densities, the value of dynamic pressure occurring in the multiphase flow increases proportionally.

Thus, the causes of dynamic loads occurring in multiphase oil and gas pipelines were investigated, and the assessment of dynamic pressure generated in multiphase flows was considered. Mathematical models have been proposed for determining dynamic pressure in multiphase flows with oil and gas as the dispersed medium, depending on the volumetric gas holdup and phase density ratios.



1÷5 - correspond respectively to $\frac{\rho_m}{\rho_q} = 25,50,75,90,120$

Figure 8. Dynamic pressure dependence on gas holdup in multiphase flow

It was determined that dynamic pressure decreases with increasing gas holdup, while the value of dynamic pressure increases with an increase in the density ratio of the liquid and gas phases.

The sixth section investigates the lateral displacement and buckling of a subsea pipeline considering the pipe–soil interaction on the seabed. In accordance with the DNV-RP-F109 approach, the combination of static, quasi-static, and time-domain dynamic analyses was considered. A 3-hour simulation period, hydrodynamic effects based on the Morison equation, and a wave model according to the JONSWAP spectrum were applied. The dependence of the passive soil resistance on displacement was also taken into account (Figure 10).

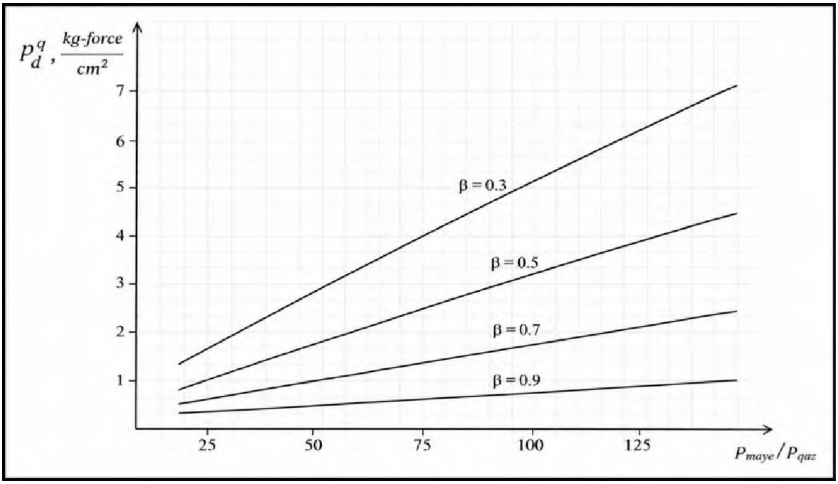


Figure 9. Dynamic pressure dependence on phase density ratio in multiphase flow

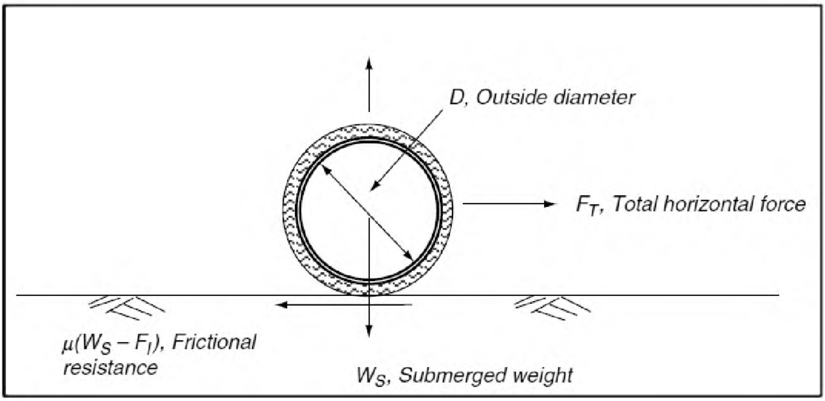


Figure 10. Stability assessment of subsea pipelines

CONCLUSIONS AND SUGGESTIONS

1. Based on the technical diagnostics of gas wells, it was determined that the flowline (Ø89 mm) of gas well No. 184, located at offshore stationary platform No. 10 (DSP-10) under the balance of the "28 May" Oil and Gas Production Department, operating at a pressure of 64 kgf/cm², is unsuitable for further operation due to the fact that its actual wall thickness is lower than the allowable wall thickness [4].

2. A method has been developed for assessing oil spills (ballast volume) into the environment under pressureless flow conditions in relief pipelines, taking into account the multiphase nature of the flow regardless of the cause of the leakage [5].

3. Based on the technical and technological diagnostic data reflecting the operational characteristics of oil and gas pipelines, the feasibility of assessing the remaining service life of pipelines using the minimum probable wall thickness and taking into account the corrosion rate has been demonstrated [11].

4. During the inspection of the underground section of the 530 mm diameter "Northern Export" pipeline at the excavation pit opened at the 14th km using the Metal Magnetic Memory method, a characteristic stress accumulation zone was detected in the pipeline. Since the detected anomaly was classified as a Group III hazard level, the pipeline section was considered suitable for operation. Considering the effectiveness of this method, its application at other SOCAR facilities has been proposed [1].

5. Based on operational data, the necessity of technological diagnostics for the deposition of hydrocarbons, water, and mechanical impurities transported with gas in pipelines subjected to phase transformations has been demonstrated [9].

6. In order to improve the operational efficiency and increase the remaining service life of subsea pipelines, the necessity and frequency of pipeline cleaning from condensate, water, and other accumulated substances have been determined based on the assessment of the allowable volume and periodicity of condensate accumulation in the pipeline, taking into account the gas flow rate. It has been established

that the cleaning frequency varies from once a month to once every 4–5 months [7].

7. The effects of dynamic loads occurring in pipelines during multiphase flow on pipeline reliability and operability have been investigated, and a mathematical model has been proposed for evaluating dynamic pressure loads depending on gas holdup and phase densities [10].

8. Using the MATLAB mathematical software, the dynamic stability of subsea pipelines was analyzed, and the lateral buckling behavior and calculations of pipelines were investigated [8].

9. The simulation of structural reliability of gas pipelines was performed using modern software tools. As a result of ultrasonic thickness measurements and flaw detection works carried out using the "Olympus 27 MG" ultrasonic thickness gauge at the excavation pit opened at the 187.74 km section of the underground "Astara-Gazimammad" gas pipeline belonging to the "Gas Export" Department, the actual wall thicknesses in the linear section of the pipeline were determined as 12.18 mm in the upper part, 11.80 mm in the side part, and 9.19 mm in the lower part of the pipe. Since corrosion cracks with a depth of 5–6 mm were detected in the lower part of the pipeline, the actual wall thickness in this section was determined to be 3.19 mm. Based on the comparison of the calculated wall thickness obtained from the mathematical analysis of the pipeline with the actual wall thickness (3.19 < 4.60), it was concluded that this section of the pipeline is unsuitable for further operation. It was also determined that the yield stress value (379 MPa) exceeds the yield strength corresponding to the physical properties of the metal (350 MPa) [1].

The main provisions and content of the dissertation are reflected in the following published works:

1. Nagizadeh, A.R. On the Application of a New Method for Pipeline Diagnostics // Azerbaijan Oil Industry, Baku, 2022, No. 9, pp. 63–67.

2. Ismayilova, F.B., Nagizadeh, A.R. Calculation of the Structural Reliability of Main Gas Pipelines Using Modern Software Tools // Proceedings of Azerbaijan Engineering Academy, Baku, 2023, Vol. 15, No. 3, pp. 59–65.

3. Nagizadeh, A.R. On the Method for Strength and Stability Calculation of High-Pressure Technological Steel Pipelines // Azerbaijan Oil Industry, Baku, 2023, No. 9, pp. 30–34.

4. Nagizadeh, A.R. Technical Diagnostic Works Performed on the Flowline of Gas Well No. 184 at Offshore Stationary Platform No. 10 of the "28 May" Oil and Gas Production Department // Proceedings of the Republican Scientific Conference dedicated to the 100th anniversary of the birth of National Leader Heydar Aliyev on the topic "Problems and Prospects of Oil Field Exploration", Baku, 2023, No. 12, pp. 148–150.

5. Ismayilov, G.G., Nagizadeh, A.R. Investigation of Accidental Oil Spills in Pipelines under Pressureless Flow Conditions // Azerbaijan Oil Industry, Baku, 2024, No. 11, pp. 22–26.

6. Nagizadeh, A.R. Analysis of Strength and Stability Calculations of Subsea Marine Pipelines // News of PANTEI Higher Technical Schools of Azerbaijan, Baku, 2024, Vol. 45, No. 15, pp. 6–14.

7. Nagizadeh, A.R., Shahlarli, M.E. Problems Related to Subsea Pipeline Technology and Their Optimization // Proceedings of the XXVII Republican Scientific Conference of Doctoral Students and Young Researchers, Part I, Baku, December 10–11, 2024, pp. 266–271.

8. Ismayilov, G.G., Shahlarli, M.E., Nagizadeh, A.R. Subsea Pipeline Lateral Buckling Analysis // International Conference on Energy and Environmental Technologies in Engineering and Architecture (ICETEA), Baku, 2024, pp. 222–226.

9. Ismayilov, G.G., Ismayilova, F.B., Naghizade, A.R. Assessment of Pipeline Remaining Service Life Based on Diagnostic Data // Scientific News, Baku, 2025, No. 2(25), pp. 57–62.

10. Ismayilov, G.G., Ismayilova, F.B., Nagizadeh, A.R. Advanced Resource Operation of Main Natural Gas Pipeline Using CFD Modeling Methods // ETARS (Scopus Q4), Baku, 2025, UDC 621.681, DOI: 10.33070, No. 2, pp. 168–174.

11. Ismayilov, G.G., Ismayilova, F.B., Nagizadeh, A.R. Analysis of Structural Reliability of Main Gas Pipelines // Latvian Journal of Physics and Technical Sciences, Latvia, 2025, DOI: 10.2478/lpts-2025-0029, No. 4, pp. 57–64.

12. Iskandarov, E.Kh. The Effect of Filling the Gas Pipeline with Condensate on Transport Pressure / M. Shukurlu, F.B. İsmayilova, A.R. Nagizadeh // Geology-Petroleum Engineering Bulletin, - Serbia: - 2025. №3, - p. 17-24.

Personal Contribution of the Applicant to the Published Work:

[1], [3], [4], [6], [12] - was performed independently.
[2], [5], [7-11] – The contributions of the co-authors are equal.

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