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THE DEFORMATION BEHAVIOUR OF THE LONG-TERM EXPLOITED PIPELINES IN SIMULATED SOIL ELECTROLYTES IMITATES

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Abstract. *Pipeline transportation of hydrocarbon energy is one of the cheapest and most environmentally friendly transport methods. In the context of the green energy transition and implementing ambitious plans to reduce carbon emissions. The issue of optimal future use of the released pipeline capacities arises. One promising option is to use existing pipeline networks to transport green hydrogen and methane-hydrogen mixtures. The pipeline steel is subject to defect accumulation during long-term operation, which causes degradation of physical and mechanical properties. The influence of operational degradation on the resistance to deformation of 19G and 17GS pipe steels in soil electrolytes of different chemical compositions was studied. It is shown that the strain growth in corrosive environments can be up to 30%, which will increase operational risks, especially in areas that run in structurally unstable soils. At the same time, the absolute values of the strain increase are in the range of 3...7% and are not very dangerous since they are within the range of tolerable damage. In the future, it will be advisable to study in more detail the behaviour of pipe steels after long-term operation in the environment of hydrogen gas and methane-hydrogen mixtures to assess the prospects for using existing pipelines for their transportation.*

Key words: *main gas pipelines, hydrogen pipeline transport, soil electrolytes, corrosion-mechanical degradation, deformation, bearing capacity.*

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1. INTRODUCTION

Assessment of the condition of long-term structures in terms of their operational safety is mainly about identifying and characterising various types of defects. At the same time, possible deterioration of the physical and mechanical properties of materials that determine their manufacturability should be considered. Recently, special attention has been paid to this problem since a significant part of the structures of responsible purpose in many branches of industry and transport have already exhausted their planned resource, which is tens of years. Such objects include the main gas pipelines of Ukraine, most of which have a service life of 30–40 years. Therefore, their performance may be lost due to metal ageing, local corrosion, and damage to both the outer and inner sides of the pipes [1]. The main factor of corrosion of the inner surface of pipes is water condensate, which accumulates salts, organic impurities, CO_2, and sulfur compounds, even in small quantities contained in purified gas [2]. Condensate can drain into the lower part of the pipe [3, 4], making this part particularly vulnerable to corrosion. Considering the intensification of the degradation of metal properties by the environment in the volume of the pipe wall, it should also be taken into account that it can be hydrogenated due to the «metal-environment» interaction [5, 6].

Many scientists have researched the operational degradation of pipeline steel, specifically in oil and gas pipelines. Most of these studies have been conducted in Eastern Europe, particularly in the countries of the former USSR, due to their well-established network of gas pipelines built in the 1960s and 1970s. In recent years, researchers have found that the most appropriate way to assess the level of destruction of pipeline material is by determining the change in mechanical indicators such as strength, impact strength, and plasticity, as well as electrochemical indicators such as OCP, corrosion potential, corrosion current, and polarisation resistance. Research has shown that various factors, such as modes, duration of operation, corrosion activity of the transported product and soil electrolyte, play a significant role in degradation processes [1, 3, 6, 7].

The study of the deformation behaviour of pipeline steels under conditions of loads and influences that simulate operational conditions will allow a more accurate assessment of the remaining resources for the safe operation of existing and new pipelines, as well as predict operational risks and assess the level of potential environmental hazards caused by the operation of these technical objects [8–10]. It is important to study the kinetics of deformation in aggressive environments because the level of damage as a result of the synergistic action of mechanical and corrosive factors increases non-linearly, so the risk of depressurisation or pipeline destruction, and therefore the associated operational risks, also increases [11–13].

It is also important to note the significant potential of the Ukrainian gas transportation system for transporting green hydrogen and methane-hydrogen mixtures to European consumers. Ukraine has the most extensive gas transportation system in Europe, which is already connected to the European system through several gas transportation corridors. At the same time, Ukraine has a significant surplus of green electricity generation during the day. Given the lack of balancing capacity, it is advisable to use the surplus of green electricity to produce green hydrogen and then transport it to the EU. However, it is important to minimise operational risks and choose the best routes at the transportation stage.

The study aims to assess the effect of long-term operation on the pipeline material's ability to resist deformation in corrosive environments that simulate soils with varying salinity levels. This assessment will help identify potential risks while transporting hydrogen or methane-hydrogen mixtures and choose the best transportation routes.

2. MATERIALS AND METHODS

17GS and 19G pipeline steels are among the most widely used materials in pipeline construction (Table 1) in Eastern Europe 30–40 years ago and were chosen as an object of research.

Table 1

Chemical composition of selected pipeline steels

Steel	C	Si	Mn	Ni	S	P	Cr	Cu
17GS	0.14–0.20	0.40–0.60	1.00–1.40	≤ 0.30	≤0.035	≤0.030	≤0.30	≤0.30
19G	0.16–0.22	0.17–0.37	0.8–1.15	≤ 0.30	≤0.035	≤0.015	≤ 0.30	≤0.30

To study the effect of material degradation on long-term resistance to deformations, a batch of samples were made from the pipe after 41 years of operation (Fig. 1). For this purpose, a series of mechanical and corrosion-mechanical tests were carried out in the corrosive media, which imitates the soil electrolytes [14–17]. It is proposed to estimate the change in the bearing capacity of the pipeline material by the value of the increase in deformation in air $\Delta\varepsilon_c$ and corrosive environments $\Delta\varepsilon_{cc}$ for pipe steels in the condition of delivery and after 41 years of operation. Previously, a study of the deformation behaviour of unoperated pipeline steel in air and in 12 model environments simulating the main types of soil electrolytes was carried out [14].To study the long-term resistance to deformations, the KN-1 installation was used [14]. Testing gas pipeline material samples in air and corrosive environments under static load, under pure bending, with automatic registration of sample deformation and electrode potential changes was performed.

For the investigation of the long-term deformation of the pipeline steel, three levels of nominal stresses were selected according to the yield limit of the pipeline material: 330, 420, and 510 MPa. To study the deformation behaviour of pipeline steel and to consider relaxation processes, the load was applied by a step method with a duration of 20 seconds. Tests were conducted in two stages to demonstrate the impact of a corrosive environment on the deformation behaviour of pipeline steel. First, tests were carried out in the air to simulate pipeline operation with an undamaged insulation coating. Second, tests were conducted in corrosive environments. (soil electrolytes imitation, Table 2). The exposure time was 300,000 minutes (200 days).

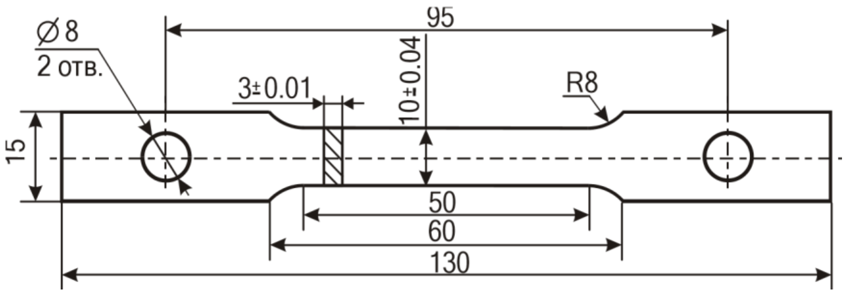

Figure 1. Scheme of a flat sample for corrosion-mechanical tests

Table 2

Chemical composition of soil electrolyte imitations (SEI)

SEI	NaCl, mol*l^{-1}	Na_2SO_4, mol*l^{-1}
1	0.01	-
2	0.05	-
3	0.1	-
4	0.005	0.005
5	0.25	0.25
6	0.05	0.05

3. RESULTS AND DISCUSSION

The effect of long-term operation on the 17GS steel. In the air, there is an active increase in deformation at the initial stage, with a further decrease in intensity for unused pipe material after 41 years of operation. (Fig. 2). The increase in deformation is 15...20%.

This deformation behaviour is not anomalous and indicates that changes in the mechanical properties of the pipe steel, which was not in contact with a corrosive environment, do not significantly worsen its operational characteristics. However, given the imperfection of anticorrosion coatings used in constructing main pipelines at the end of the 60s and 70s of the last century, such a situation is quite hypothetical. Therefore, tests in the air are required to separate the effect of a corrosive environment.

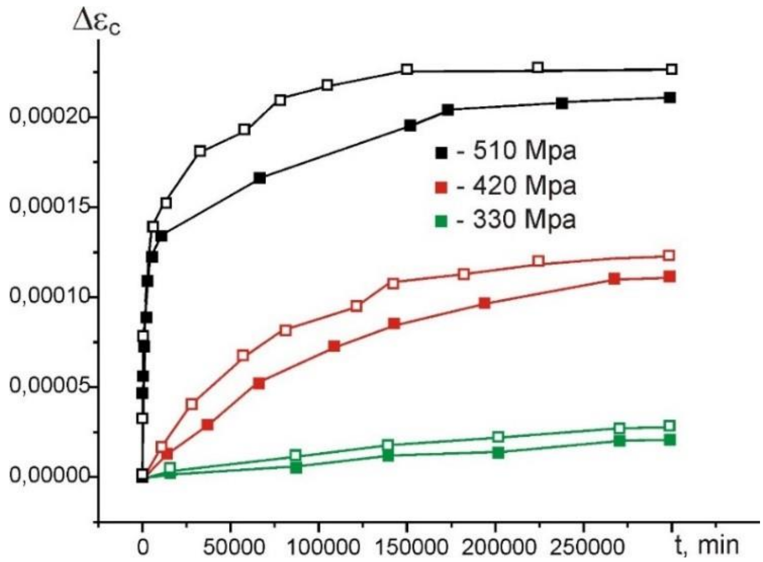

Figure 2. Kinetics of pipeline steel deformation in the air: filled symbols – new steel, clear symbols – exploited steel

With an increase in the value of nominal stresses, the intensity of the deformation process increases. A step on the deformation curve is observed at the highest load, close to the strength limit. Here, it should also be noted that such steps were recorded at a lower level of nominal stresses for the operated steel. This deformation behaviour can be caused by the propagation of microcracks or the coalescence of diffuse damage [18–20]. Since the exploited steel has a much larger number of accumulated scattered damages and microcracks in the state of nucleation, a lower level of applied stresses is necessary for their development. Similar deformation behaviour is also confirmed by other studies [20, 21].

As the value of nominal stresses decreases, the growth rate of deformation decreases, and when approaching the yield point, the kinetics becomes practically linear. The character of the pipe steel deformation process kinetic changes depending on the level of applied mechanical stresses. At their maximum level, the deformation kinetics is three-stage:

- accelerated deformation, which is 10–15% of the exposure time;
- less active but still intense deformation, which is 45–60% of the exposure time;
- plateau stage, at which the deformation process stabilises, and the increase in deformation becomes almost imperceptible. This stage takes 25–40% of the exposure time.

To predict the processes of long-term deformation of pipelines under stress, it is proposed to use the angle of inclination of the final section of the deformation curve as one of the criteria. For all corrosive environments, an increase in this indicator compared to air was recorded for steel in the condition of delivery [14] and pipe steel after 41 years of operation. When comparing this indicator in one corrosive environment, it is higher for long-term operated steel, which indicates a greater danger of bearing capacity loss.

Deformation behaviour in model environments that simulate soils with chloride salinity (Fig. 3 – Fig. 5) demonstrates an increase in deformation during the entire exposure time. On deformation curves, unlike air, there are no steps. This behaviour of pipeline steel can be explained by the plasticisation of the surface layers of the metal due to the influence of the Rebinder effect [14, 22, 23]. Under such conditions, plastic deformation of the metal will occur instead of the growth of microcracks in places of corrosion damage to the surface.

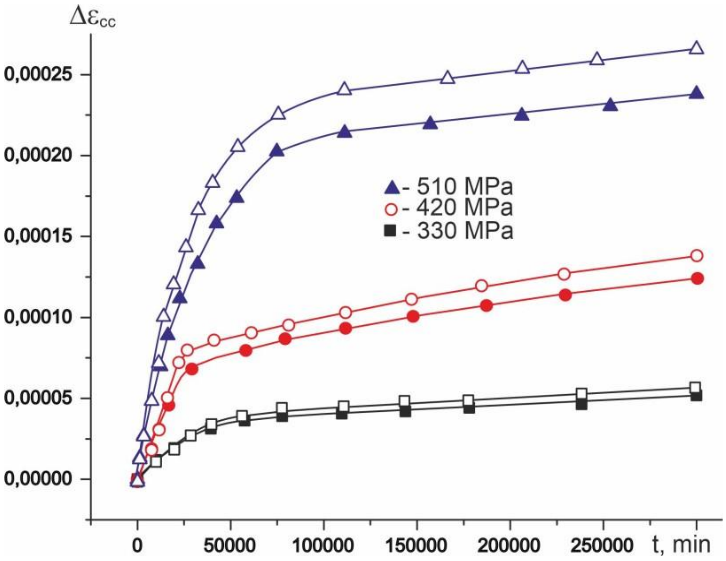

Figure 3. Kinetics of pipeline steel deformation in SEI1:
filled symbols – new steel, clear symbols – exploited steel

Over time, the rate of deformation of pipe steel decreases. However, for all load levels, even for the smallest one, the deformation process in a corrosive medium does not reach an equilibrium value within the experimental exposure. This is the main difference compared to the results obtained in air tests [14].

Such deformation kinetics is explained by the simultaneous influence of mechanical loads and a corrosive environment on pipe steel. Deformation of the metal surface damages the integrity of the coating from insoluble corrosion products. It opens access to the corrosive environment to the unpassivated metal surface. In this way, corrosion processes are activated, and the metal surface undergoes additional local damage. These damages can become centres of microcracks, which can cause corrosion failure of the pressure pipes. Additionally, they can promote hydrogen adsorption and act as hydrogen traps. It is important to highlight the impact of hydrogenation and hydrogen embrittlement processes separately. The hydrogen embrittlement of various types of steel has been widely studied [5–6]. However, there has not been sufficient study on the effect of hydrogen on pipeline metal that has been in operation for 30 (40) years [24–27]. Considering the scattered damage of pipe steels due to operational degradation, which contributes to the penetration of hydrogen into their structure, it can be assumed that there will be a significant reduction in the resource of safe operation of pipelines [1, 3, 28, 29].

Hydrogen embrittlement is a significant danger for steels in long-term operations due to the hydrogenation process. Scattered damage accumulates in the metal structure due to operational degradation, which serves as a trap for hydrogen atoms [3, 25, 28].

A comparison of the results of the study of the deformation behaviour of steels in neutral and acidic corrosive environments will make it possible to distinguish the role of the hydrogen factor [9, 14]. This problem is particularly relevant during the transition to green and renewable energy, particularly using hydrogen and methane-hydrogen mixtures as energy carriers. For their transportation, the cheapest and most ecological type of transport is the pipeline. The existing network of gas pipelines in European countries is quite extensive, and capital investments in its modernisation for the transportation of hydrogen or methane-hydrogen mixtures are acceptable. One of the main obstacles to converting gas pipeline networks is the increased sensitivity of long-term steel used for hydrogen embrittlement.

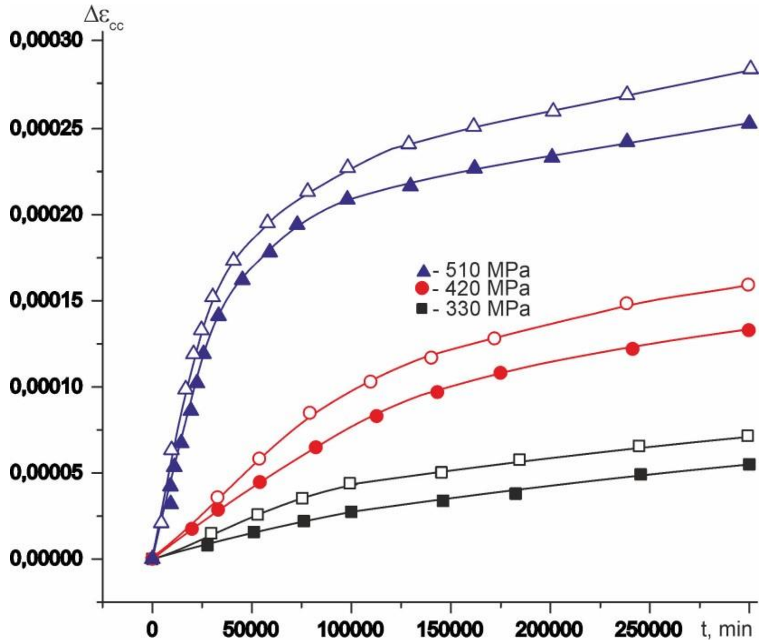

Figure 4. Kinetics of pipeline steel deformation in SEI2:
filled symbols – new steel, clear symbols – exploited steel

As a result of the joint influence of corrosive environments and mechanical stresses, the development of existing and new defects takes place [30–32], which reduces the resistance of pipe steels to long-term deformations. At the tops of crack-like defects due to the hydrolysis of corrosion products, the pH of the environment becomes acidic, which will cause the release of hydrogen, the intensification of the hydrogenation process, and the occurrence of hydrogen embrittlement.

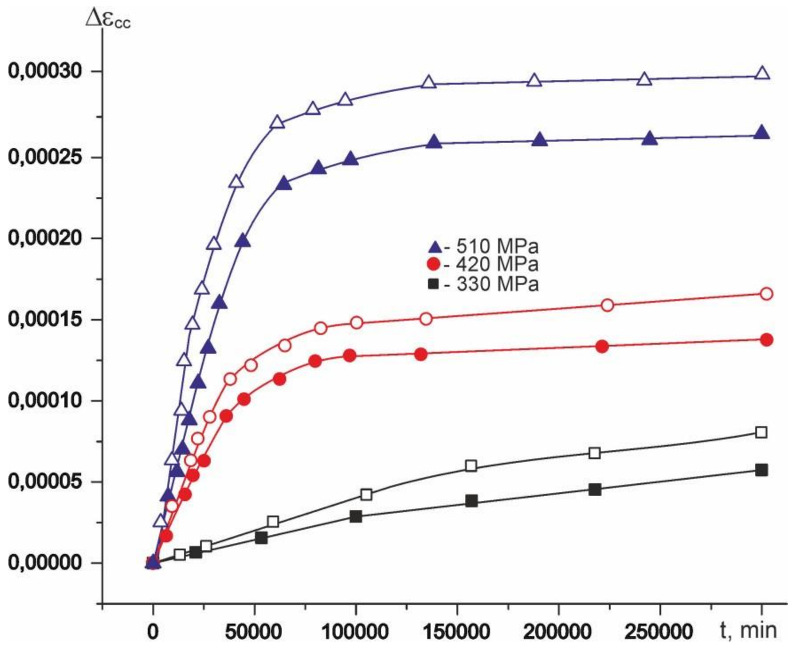

Figure 5. Kinetics of pipeline steel deformation in SEI3:
filled symbols – new steel, clear symbols – exploited steel

Such potential operational risks must be predicted and warned on time. At the same time, conducted studies [2, 3, 6, 7, 9, 10, 18–21, 33, 34] show that long-term operated pipelines still have a significant safety margin. The study of the deformation processes of degraded steels in corrosive environments will make it possible to optimise the modes of transportation of hydrogen and methane-hydrogen mixtures, reducing operational risks to acceptable levels.

For all applied stress levels, there is an increase in deformation value without steps on the deformation curves. This behaviour of the pipe material indicates the emergence of new corrosion damages and the deepening of existing ones. At the same time, the absence of steps on the deformation curves indicates the absence or insignificant effect of embrittlement of degraded steel. On the other hand, the deformation process does not enter a stationary state, as evidenced by the inclination angles of the final sections of curves. Therefore, there is a risk of developing local corrosion damage up to the depressurisation of the pipeline. The increased deformation for all applied loads increases compared to air. The absolute increase is directly proportional to the applied stresses.

Deformation curves in chloride environments have a damping character. However, the inclination angles of the final part of the curve (damping criterion) are greater than in air, indicating the long-term nonstationarity process. Under such conditions, the pipeline's ability to withstand long-term loads decreases. Separately, the high rates of nonstationarity of deformation processes at the lowest level of applied stresses should be noted. This behaviour of the pipeline material can lead to a loss of bearing capacity under sudden acyclic overloads, for example, during landslides and subsidence [35].

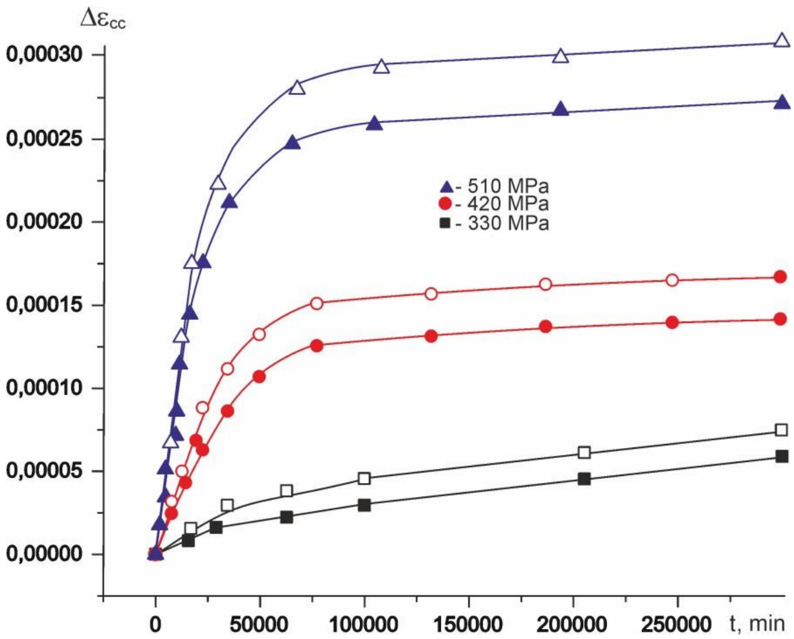

Figure 6. Kinetics of pipeline steel deformation in SEI4:
filled symbols – new steel, clear symbols – exploited steel

In imitations of soil electrolytes with mixed (chloride-sulfate) salinity, more significant increases in deformation were recorded compared to chloride salinity (Figs. 7–9). It is also possible to note significantly higher deformation increments than air, especially in SEI6 (Fig. 8).

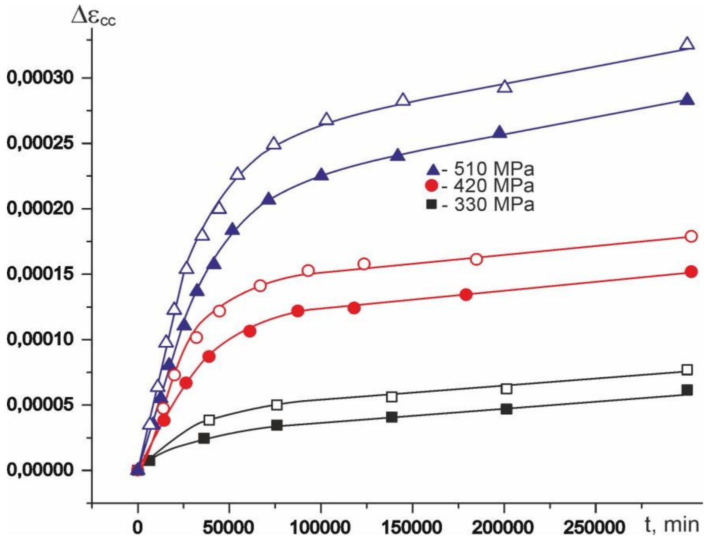

Figure 7. Kinetics of pipeline steel deformation in SEI5:
filled symbols – new steel, clear symbols – exploited steel

It is also necessary to note the higher nonstationarity of the process in SEI of mixed anionic composition compared to chloride media [9, 14]. This is especially noticeable for minimum and medium stress levels. This behaviour of pipe steels seems to be caused by the mutually reinforcing effect of chloride and sulfate ions, which accelerates corrosion processes and promotes their localisation [36]. This leads to increased risks of nucleation and the development of crack-like defects in degraded pipe steels in places of local corrosion damage [20–22].

The long-term increase in deformation without visible attenuation in SEI5 and SEI6 is also dangerous. Such deformation behaviour indicates high risks of loss of bearing capacity of long-term operated pipelines laid in highly mineralised soils, which may become structurally unstable due to sudden waterlogging. Also, the increased risk of an emergency can be caused by a sudden acyclic overload (terrorist attack, military actions, etc.) [37, 38]. This is because the mechanical properties, especially impact toughness, have deteriorated. Hydrogen and methane-hydrogen mixtures are more explosive than natural gas, which increases potential operational risks during transportation through structurally unstable or corrosive soils.

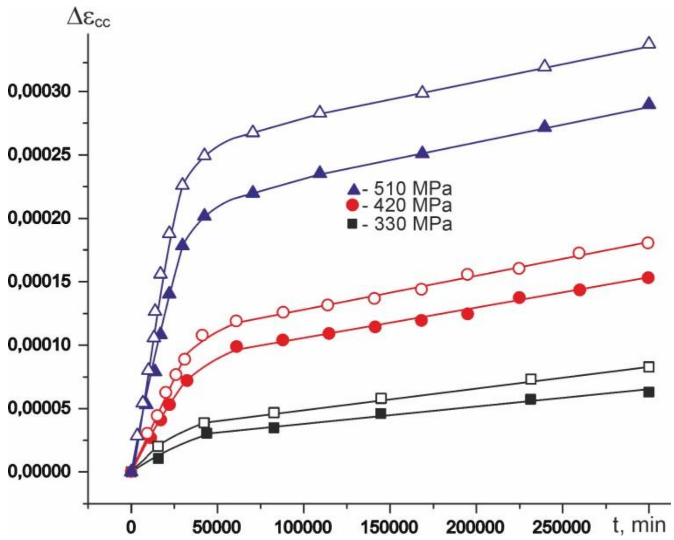

Figure 8. Kinetics of pipeline steel deformation in SEI6:
filled symbols – new steel, clear symbols – exploited steel

The effect of long-term operation on the 19G steel. In SEI with a chloride type of salinity, the deformation kinetics of 19G steel is slightly different from the kinetics of 17GS steel. There are no ledges on the deformation curves for operated and unoperated steel. The absolute and relative values of the increase in deformation for 19G steel for all load levels are greater than for 17GS steel. In addition, at the initial stage, the deformation of 19G steel occurs 20–30 percent faster than 17GS steel (Fig. 9–11).

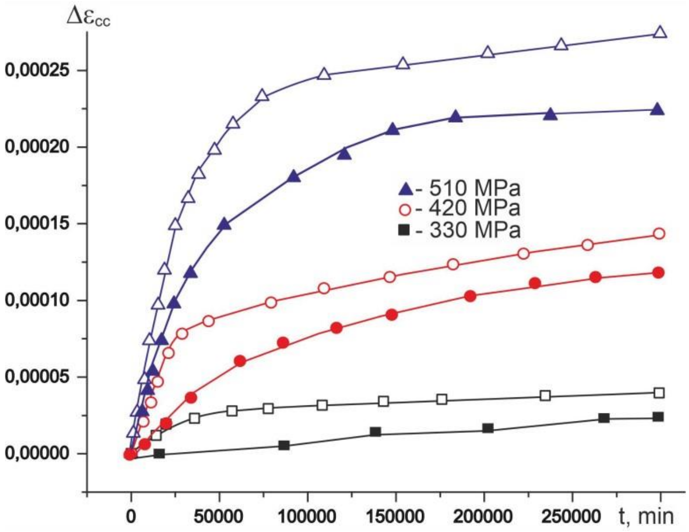

Figure 9. Kinetics of pipeline steel deformation in SEI1:
filled symbols – new steel, clear symbols – exploited steel

Comparing the deformation kinetics of long-term operated and not-operated 19G steel, it was established that the deformation process becomes longer due to the influence of operational degradation. After analysing the final sections of the deformation curves, larger values of the inclination angles were recorded for the long-term operated steel, which indicates a decrease in the ability of the metal to resist long-term deformations. This tendency is especially pronounced in SEI2.

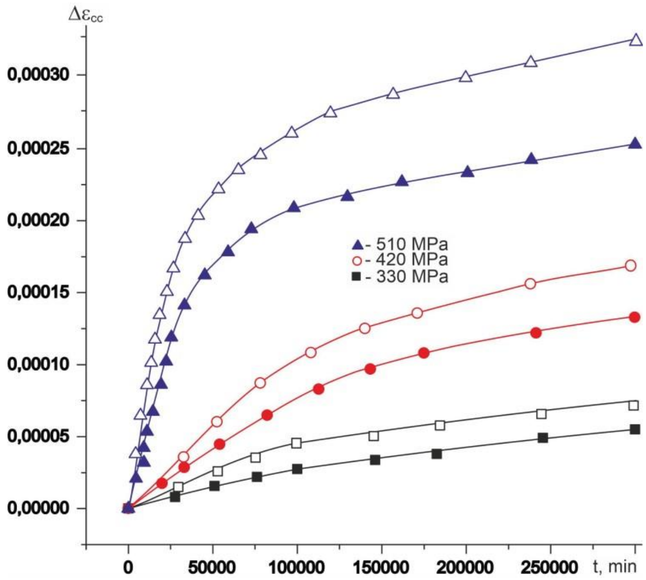

Figure 10. Kinetics of pipeline steel deformation in SEI2:
filled symbols – new steel, clear symbols – exploited steel

During further operation, this behaviour of pipeline steel can lead to emergencies if the pipeline is subjected to sudden loads or overloads [39, 40]. Thus, in neutral chloride environments, the degradation of the bearing capacity indicators of steel 19G is 7–15% higher than for 17GS.

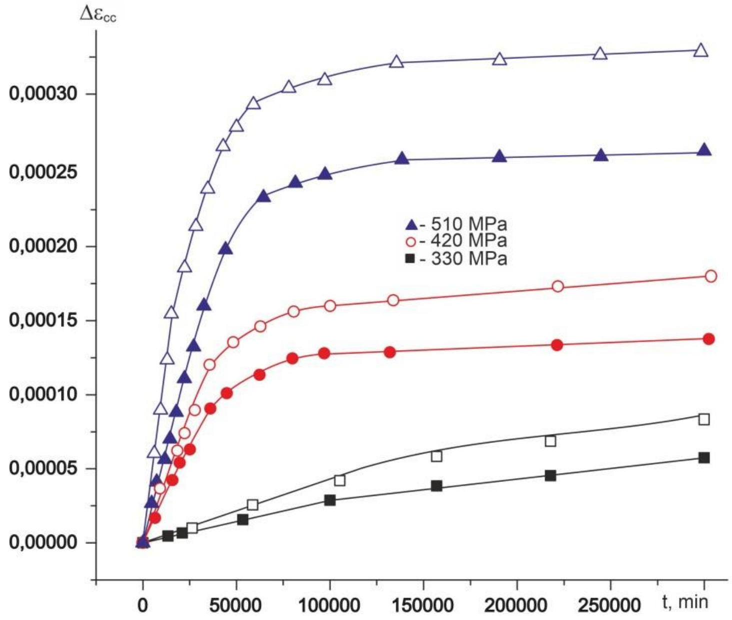

Figure 11. Kinetics of pipeline steel deformation in SEI3:
filled symbols – new steel, clear symbols – exploited steel

In simulated groundwater with a mixed ionic composition (chloride-sulfate), the deformation kinetics of 19G steel has the following differences from that of 17GS steel: a higher rate of deformation at the initial stage was recorded, as well as an increase in the absolute values of deformations and their relative growth (Fig. 12 – Fig. 14).

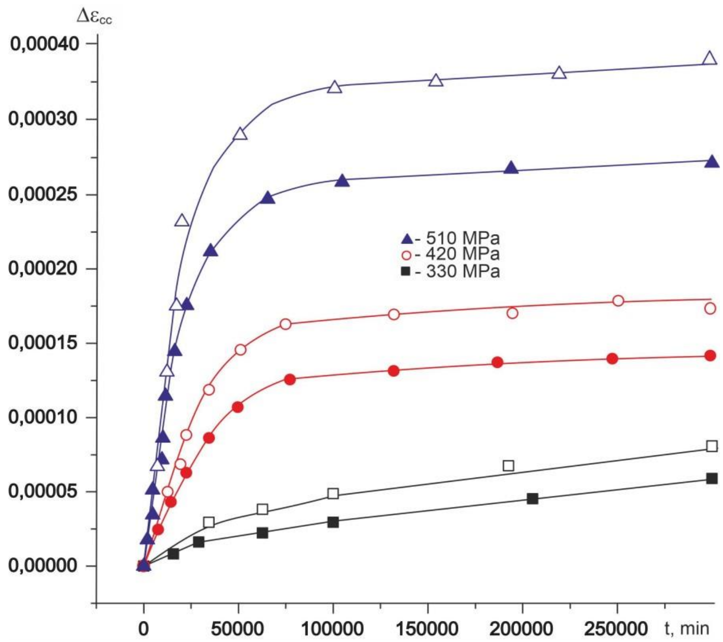

Figure 12. Kinetics of pipeline steel deformation in SEI4:
filled symbols – new steel, clear symbols – exploited steel

Additionally, the SEI5 and SEI6 exhibit significant nonstationarity, as confirmed by the slope angles of the final sections of the deformation curves. This behaviour of 19G pipe steel indicates an increased risk of corrosion damage and a decreased long-term resistance to deformation in the case of defective anticorrosion coating.

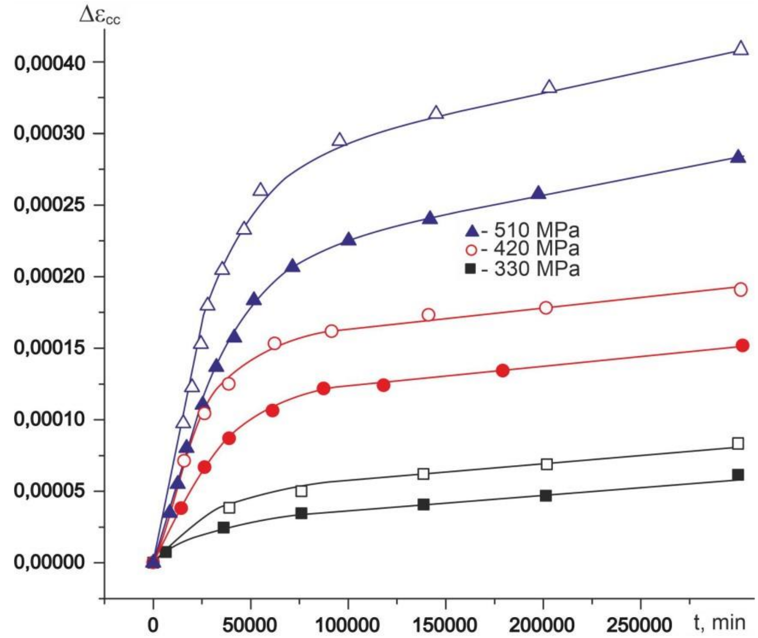

Figure 13. Kinetics of pipeline steel deformation in SEI5: filled symbols – new steel, clear symbols – exploited steel

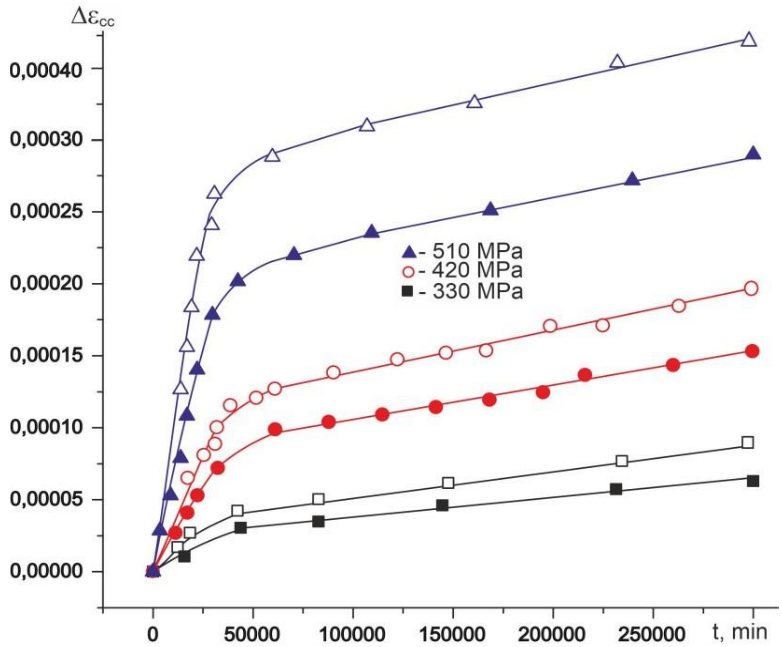

Figure 14. Kinetics of pipeline steel deformation in SEI6: filled symbols – new steel, clear symbols – exploited steel

The influence of long-term operation on the deformation resistance of 17GS and 19G pipe steels was investigated. The soil electrolytes with an increased risk of developing long-term deformation processes in pipeline sections with damaged insulation coating were identified. It is shown that 17GS steel is less sensitive to corrosion and mechanical degradation processes. It is shown that the absolute increase in deformation in simulated soil electrolytes is not significant and that the main potential operational risks of hydrogen/hydrogen-methane mixture transport are associated with the simultaneous action of several negative factors (structural degradation, additional soaking and subsequent embrittlement of pipe steel during hydrogen transport, sharp acyclic loads, etc.). Given a preliminary assessment of the degradation of the physical and mechanical properties of pipe steels and the corresponding adaptation of the pumping modes, the use of existing gas pipelines in Eastern Europe to transport hydrogen and methane-hydrogen mixtures is reasonable. The potential of the Ukrainian gas transportation network, which has long operated in the mode of exporting natural gas to European consumers, should be highlighted separately.

4. CONCLUSIONS

The study investigated the impact of operational degradation of pipeline material on its bearing capacity in soil electrolytes with monoanionic (chloride ions as the corrosive component) and polyanionic (chlorides and sulfates as the corrosive component). The results showed that the deformation can increase up to 30% compared to non-operational steel.

The highest risks of accidents for both studied steels were observed in SEI2, SEI5, and SEI6 soil electrolytes. These trends pose a significant risk to pipelines installed in unstable soils and mountainous areas prone to landslides.

The deformation rate of pipe steels after 41 years of operation in corrosive environments at three levels of mechanical load is 3.7%. While this rate is within the permissible damage tolerance range, it is still a cause for concern. The rise in operational risks is due to the combined effects of several stress factors, such as the degradation of physical and mechanical characteristics resulting from long-term operation, exposure to corrosive environments, constant and variable mechanical loads, and hydrogenation.

In the future, it is necessary to conduct a more detailed study of the behaviour of pipe steels following long-term operation in hydrogen gas and methane-hydrogen mixtures. This will help assess the feasibility of using existing pipelines for transportation.

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ДЕФОРМАЦІЙНА ПОВЕДІНКА ДОВГОЕКСПЛУАТОВАНИХ ТРУБОПРОВОДІВ В ІМІТОВАНОМУ ҐРУНТОВОМУ ЕЛЕКТРОЛІТІ

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Резюме. *Досліджено деформаційну поведінку сталей магістральних трубопроводів 17ГС та 19Г, які перебували в експлуатації понад 40 років, у середовищах, що імітують ґрунтові електроліти. У процесі тривалої експлуатації сталі труб накопичують мікродефекти, що спричиняють деградацію фізико-механічних властивостей. Особливу небезпеку становлять ділянки трубопроводів, розташовані в нестабільних ґрунтах або місцях із пошкодженим антикорозійним покриттям. Для оцінювання стійкості матеріалу до деформацій проведено серію корозійно-механічних випробувань на спеціальних зразках за* *різних рівнів навантаження (330, 420, 510 МПа). Результати свідчать, що після 41 року експлуатації сталь демонструє зростання деформації до 30% в агресивних середовищах. Абсолютне збільшення деформації становить 3–7%, що є допустимим, однак це свідчить про потенційне зниження несучої здатності. Найнебезпечнішими середовищами виявилися SEI2 (0.05 M NaCl), SEI5 і SEI6 (змішані хлоридно-сульфатні електроліти), які спричинили прискорену деформацію й посилену нестабільність процесу. Сталь 17ГС менш чутлива до деградації, ніж 19Г, що пояснюється відмінностями в хімічному складі та структурі. Зокрема, у сталі 19Г на початковому етапі деформація відбувається на 20–30% швидше. Встановлено, що воднева деградація й накопичення локальних пошкоджень можуть значно знизити термін експлуатації. Водень, проникаючи в мікропорожнини та дефекти, сприяє окрихченню металу, що особливо критично в умовах несподіваних перевантажень – природних катаклізмів, воєнних дій чи аварій. Дослідження вказують на необхідність урахування мультифакторного впливу – механічних навантажень, довготривалої експлуатації, середовища з високою корозійною агресивністю та дії водню. Усі ці фактори в сукупності визначають рівень експлуатаційного ризику. Запропоновано використовувати нахил фінального відрізка кривої деформації як індикатор для прогнозування вичерпання ресурсу трубопроводу.*

Ключові слова: *main gas pipelines, hydrogen pipeline transport, soil electrolytes, corrosion-mechanical degradation, deformation, bearing capacity.*

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