Identification of the root causes of accidents at hazardous production facilities of the fuel and energy complex

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Abstract. The article presents the results of the analysis of statistical data on accidents at the facilities of the main pipeline gas transportation for the period from 2008 to 2018. It has been established that the dynamics of accident rates has a cyclical wave-like character. In the course of analyzing information on accidents that occurred during the study period, groups of the main causes of accidents in the main pipeline gas transportation were identified. In addition, in the course of the study, the nature of the occurrence of stress corrosion cracking was studied in detail, and the root factors that led to the occurrence of accidents for this reason were identified. With the help of regression analysis, a functional relationship was established between the number of accidents due to corrosion destruction and hidden defects, which included defects of the pipe manufacturer and defects in construction and installation works.

1. Introduction
The gas transmission system is a complex technical system strategically important for the development of industry and energy supply in Russia. As the technical and economic conditions for the development of the oil and gas complex change, it is necessary to solve more and more complex problems to ensure the uninterrupted and safe operation of gas trunk lines. One of the priority areas of companies engaged in gas transportation activities is to prevent accidents and reduce the amount of potential material damage from accidents.

Thus, the operating organizations are required to carry out large-scale work to ensure the industrial safety of gas transmission facilities at all stages of its life cycle. To determine the goals, priority areas and main tasks, as well as to develop a strategy to increase the level of industrial safety of facilities, a detailed analysis of all possible factors and conditions affecting the accident rate of gas transmission network facilities is required.

2. Materials and methods
To establish the reasons that have a negative impact on the level of industrial safety of gas transmission system facilities, an analysis of the statistical data on accidents in this industry was carried out on the basis of information provided in the annual reports of the Federal Service for Environmental, Technological and Nuclear Supervision for the period 2008 - 2018 [1]. In addition, the data on accidents presented on the official website of Rostekhnadzor in the section “Lessons learned from accidents” [2], as well as information bulletins [3-8] were considered.
Since the absolute number of accidents does not allow obtaining an objective picture of the accident rate at gas transportation facilities, since the length of the main gas pipelines is not constant, this study uses the specific accident rate, which is the number of accidents per thousand kilometers of a gas pipeline.

To identify the functional relationship between the number of accidents that occurred as a result of corrosion destruction and the number of hidden defects (factory defects and defects in construction and installation works), a regression analysis was carried out using the MS Excel analysis package, as a result of which a mathematical model was built and its statistical reliability was determined.

3. Results
During the analysis of the statistical data on accidents, it was found that the dynamics of the specific frequency of accidents on the main gas pipelines for the period under study has a wave-like character (figure 1).

![Figure 1. Dynamics of the specific indicator of accidents on main gas pipelines for the period 2008-2018.](image)

In total, 127 accidents were recorded during the study period. From the diagram shown in figure 1, it can be seen that the highest specific accident rate is observed in 2008 (0.127 accidents / thousand km). The decrease in the specific indicator of accidents on main gas pipelines from 2008 to 2010 (0.054 accidents / thousand km.) Is associated with the strengthening of measures for technical diagnostics using the in-line inspection method. In-line diagnostics is the most effective way to monitor the technical condition of main gas pipelines to detect defects in the pipe body, welded joints and eliminate them in the course of repair and maintenance work. Because of overhaul and current repairs using in-line diagnostics, a significant decrease in the number of accidents occurred.

In 2011 and 2012 an increase in the investigated accident rate is observed, which is associated with the discrepancy of some of the pipelines with the structural and technical requirements, which, in turn, makes it difficult to carry out in-line diagnostics (the presence of unequal pipes and shut-off valves, the inconsistency of the radii of the pipe turning angles, the presence of backing rings previously used in pipe welding, lack of chambers for launching and receiving in-line diagnostics devices).

After 2010, there has been an increase in the rate of wear of the fixed assets of the gas transmission system. The same reason is due to a significant increase in the accident rate at gas transmission...
facilities in 2018 - if in 2011 the share of gas pipelines with a service life of 50 years or more was 3%, then in 2018 the share of these pipelines was 18%.

The analysis of the accident rate for 2008-2018 shows that the main reason for the violation of the integrity of the main gas pipeline is the intensive development of corrosion processes, mostly stress corrosion cracking (SCC) or the so-called stress corrosion. The share of accidents that occurred in the period 2008-2018 for this reason, it is 52.4%.

The dynamics of accidents due to corrosion destruction (figure 2) has a cyclical wave-like character. Since 2015, there has been a downward trend in the number of accidents for this reason, which can be associated with the active overhaul of insulating coatings since the early 2000s, as well as current repairs based on the results of in-line diagnostics.

![Figure 2. The number of accidents caused by corrosion damage on main gas pipelines, 2008-2018.](image)

Insufficient protection of main gas pipelines from corrosion processes is mainly associated with the loss of the quality of the film insulating coating on gas pipelines commissioned over 25 years ago. So, in the period from 1991 to 1996, the share of accidents due to corrosion destruction in the total accident rate balance of PJSC "Gazprom" was about a quarter, from 1998 to 2003 - a third, and from 2008 to 2018 - more than half of the total number of accidents.

The main factors that determine the conditions for the occurrence of stress corrosion are: the presence of high tensile stresses in the pipeline wall; unsuitable condition and poor quality of insulating materials; contact of the pipe with the environment (soil, water) [9].

Analysis of the statistical data on accidents on domestic and foreign gas pipelines shows that cracking of the metal of pipelines most often occurs near compressor stations (at a distance of 10-30 km along the gas flow), and in some cases in places where pipelines turn, that is, where the temperature gas, respectively - hot walls of the gas pipeline and the highest working pressure, which cause stresses in the wall of the pipeline [10].

The acting loads play a decisive role in the emergence and development of SCC. That is, to activate the process of corrosion cracking of the metal, the presence of surface or internal tensile stresses is necessary. An increased stress-strain state in the pipe metal can be caused both by the effect of the working pressure and gas temperature, and by construction and installation works (CMP) with deviations from the project, as a result of which the position of the pipe profile does not correspond to
the design solution, which leads to additional loads. In addition, in practice, there are fractures caused by the presence of residual stresses arising during the production and processing of metal.

Thus, stress corrosion cracking is possible under the combined effect of external and internal factors, such as the low quality of the pipe metal, characterized by the peculiarities of the chemical and phase composition that contribute to the formation of micro cracks, the contact of the metal surface with an aggressive corrosive medium, and the critical level of external and internal loads. It should be noted that with the simultaneous effect of static stresses and a corrosive environment, a stronger deterioration in the mechanical properties of the metal is observed than would occur during the separate action of these factors.

The initiation of cracks during stress corrosion can be caused by the presence of a poor-quality welded joint in the presence of lack of fusion and lack of penetration in the root of the weld, which cause stress concentration; external mechanical damage to the pipe metal that does not go beyond the tolerances, the stressed state of the gas pipeline section, created as a result of deviation from the project during construction (deviation of the pipe axes).

4. Discussion
When analyzing the causes of accidents in main gas pipelines, it is necessary to take into account that, as a rule, each accident is the result of a combination of a number of undesirable events. The multifactor nature of the causes of stress corrosion on gas pipelines makes it difficult to find out the mechanism and patterns of pipeline corrosion.

In order to identify the root causes of accidents caused by corrosion destruction, the results of investigations of emergency failures of the main gas pipeline published on the Rostekhnadzor website in the section "Lessons learned from accidents in the oil and gas complex" were considered and analyzed [2]. The pie chart in figure 3 shows the distribution of accidents due to corrosion damage, depending on the root cause of their occurrence.

![Pie chart showing distribution of accidents due to corrosion damage](image)

**Figure 3.** Factors leading to the destruction of main gas pipelines due to corrosion.

Of all accidents that occurred in the period from 2014 to 2018, in 81.6% of cases, corrosion destruction occurred due to internal hidden defects, among which, in turn, the following stand out: 40.8% of cases - a factory defect (as a rule, this is a defect of a longitudinal factory seam), 18.5% - welding defects (non-compliance with welding technology during construction), 11.1% - mechanical damage to the pipeline during construction (dents, scuffs, scratches), 11.1% - retreat from design decisions, 18.6% - corrosion factors (soil corrosiveness, product temperature, operating time, etc.).
decisions. The last three groups can be attributed to defects in construction and installation work (caused by poor quality work during construction and subsequent repairs).

The functional relationship between the number of accidents that occurred on the main gas pipeline as a result of corrosion destruction and the number of hidden defects (the number of factory defects and the number of violations during construction and installation works) can be described by the following equation obtained as a result of regression data analysis:

$$ Y = 2.7368 + 0.4737 \times X_1 + 0.7368 \times X_2, $$

where $Y$ is the number of accidents that occurred on the main gas pipeline as a result of corrosion damage; $X_1$ is the number of accidents, the root of which are factory defects; $X_2$ is the number of accidents, the root cause of which is defects in construction and installation works.

The statistical significance of equation (1) was checked using the coefficient of determination $R^2$, F-Fisher's test and the confidence interval for the regression coefficient. It was found that the calculated parameters of the model obtained in the course of the regression analysis explain the relationship between the above parameters by 98%. During the assessment of the reliability of the results of the regression analysis, it was found that the values of the lower and upper boundaries of the confidence interval of the predictors $X_1$ and $X_2$ do not overlap 0, and the Fisher's calculated test is higher than the critical one ($F_{\text{calc}} > F_{\text{crit}}$), therefore, the model is statistically significant.

It should be noted that in order to prevent the occurrence of the above factors, in which there is a risk of accidents due to corrosive destruction, careful construction control and supervision are required during the installation of gas pipelines, the obligatory conduct of regular in-line diagnostic examinations using modern methods and means, as well as the proper quality of inspection and technical control during the supply of materials and equipment.

5. Conclusion

At the facilities of the main pipeline gas transportation for the period from 2008 to 2018 in 127 accidents were recorded, the dynamics of a wave-like nature was noted: several periods with peaks of accidents in 2008, 2012, 2015 and 2018 were identified. The accidents are classified into four groups depending on the main causes of accidents at the facilities of the main pipeline gas transportation: corrosion destruction, incl. stress corrosion cracking, construction defects (defects in construction and installation works, including welding defects), a generalized group of mechanical damage, including accidental damage to the pipeline during excavation in the buffer zone and mechanical damage resulting from the effects of natural phenomena), manufacturing defects. More than half of the registered accidents (52.4%) are caused by metal corrosion; due to construction defects (marriage of construction and installation works, non-compliance with welding technology) - 26.2% of accidents, due to external hazards associated with mechanical damage to the gas pipeline - 12% of accidents and 6.4% of accidents occurred as a result of factory defects.

In the framework of this study, a regression analysis of data on the number of accidents that occurred on the main gas pipeline as a result of corrosion destruction and the number of hidden internal defects was carried out. As a result of assessing the statistical reliability of the obtained model, it was found that the equation is statistically significant and explains by 98% the relationship between the number of accidents that occurred on the main gas pipeline as a result of corrosion destruction, the number of factory defects and the number of violations during construction and installation works.

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