Main patterns of stress corrosion forming the basis for control, evaluation and deceleration methods

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Abstract. The most effective methods of control during incubation of development and cracking were systematized and proposed on the basis of the developed physical model of corrosion cracking of main gas pipelines under stress. It was established that this is one of the most advanced methods for testing gas pipelines for stress corrosion cracking – this is a magnetic location method.

1. Introduction
Monitoring of a pipeline subject to stress-corrosion involves monitoring the development of the process, timely detection of defects. Once defects and other deviations from design standards are identified, it is necessary to assess the risk of these deviations and, if necessary, to take measures to eliminate them. If they cannot be eliminated, it is necessary to define safe modes of operation with these deviations. If these modes do not meet the requirements, the pipeline must be stopped. In many cases, it is impossible to immediately close the gas pipeline. It is then necessary to evaluate the safety time margin during which the pipeline can operate under all types of compensatory safety measures. The remaining pipeline resource should also be assessed for a reasonable distribution of survey periodicity [1-8]. Therefore, it is necessary to develop methods to combat the phenomenon of stress corrosion in several areas:
- calculation methods that allow assessing the real danger of accumulated failures;
- diagnostic methods to detect processes both during the incubation period and during the growth of stress corrosion cracks;
- methods of suppression of growth of corrosion defects under stress.
- methods of stress corrosion suppression during the incubation period [9, 10]. The earlier studies made it possible to establish the main patterns of stress corrosion of main gas pipelines, to develop and propose standards for monitoring, evaluation and suppression of stress corrosion of main gas pipelines for practical application [11, 12].

2. Methods and Materials
The main patterns of stress corrosion forming the basis for control, evaluation and deceleration methods are as follows:
- embrittlement and cracking of the pipe metal is associated with hydrogen accumulation in the metal;
- only atomic hydrogen formed on the surface of the pipe can penetrate the metal of gas pipelines;
- electrochemical protection of pipelines – a factor that accelerates corrosion cracking under stress;
groundwater is the source of atomic hydrogen. Hydrogen is released in places with a delaminated insulation coating under the influence of the cathode potential; another accelerating factor is high tensile stress in the pipe wall.

The rate of development of stress corrosion cracking is determined by external and internal factors in relation to the pipe metal.

External factors determine the rate of atomic hydrogen release on the metal surface. These include the state of the insulation coating (damage, lack of adhesion), the state of the pipe metal surface, the presence of soil moisture on the pipe surface, the concentration of active substances in groundwater, the acidity of the medium (pH), humidity, the resistivity of the soil, the “pipe-ground” potential difference.

Internal factors determine the rate of hydrogen penetration into the metal and the processes occurring inside the metal. These include the chemical composition and structure of the metal, as well as the stress state. At the same time, both external and internal stresses, including those acting at the level of crystals and dislocations, play a significant role.

Some factors, such as temperature, affect all processes both outside and inside the metal.

There are three periods of stress corrosion development: incubation period, crack growth period, pipeline rupture.

The incubation period is accompanied by:
- formation of atomic hydrogen on the pipe metal surface;
- penetration of hydrogen into the metal;
- processes at the microstructure level.

As a result of these processes, the pipeline undergoes the following changes over 10-15 years of operation:
- pipeline metal is saturated with hydrogen, wherein the surface layers of the metal are more intensively saturated with hydrogen. As a result, a significant gradient of hydrogen concentration along the thickness of the pipe wall appears;
- mechanical properties of the pipeline metal change. The higher the hydrogen concentration, the lower the ductility. As a result, the outer layers of the pipe wall become brittle, the inner layers retain plasticity within the normal range.

The period of crack growth is accompanied by:
- deceleration of bonds in sections of brittle metal;
- combination of small cracks into larger cracks;
- growth of cracks at preservation of metal brittleness in depth and under stress.

As a result, a network of surface cracks appears in some sections of the pipe wall. This period lasts 5-7 years.

Pipe rupture occurs when one of the cracks reaches a critical size. Since the pipelines have a safety factor of about twice as high, the critical depth of the crack is about half the wall thickness.

Below are the most likely sections for the development of stress corrosion cracking:
- in areas with the access of groundwater and moisture to the metal surface of pipelines (defects in the insulation coating, insulation coating has lost adhesion to the metal);
- at high corrosion activity of soil (specific electrical resistance of soil less than 20 Ohm-m);
- in areas where the stress state of the pipeline is high (one of the stress components exceeds 0.7 of the metal yield strength).

The experience shows that:
- in most cases the source of destruction is located at the bottom of the pipe, mainly in the range of 5-7 hours;
- no stress corrosion occurs in air sections of pipelines;
- development of stress corrosion cracking is not necessarily related to the presence of stress concentrators and other types of defects;
- presence of a stress concentrator may accelerate the development of stress corrosion cracking in a certain section.

2.1. Methods of identifying potentially hazardous areas during the incubation period of stress corrosion development.

These methods include the monitoring of the following characteristics:
- state of insulation coating, detection of coating defects, determination of “pipe-soil” transient resistance, assessment of adhesion to pipe metal. These characteristics determine the access of the elements contained in the groundwater to the pipeline metal surface, and hence, the possibility of atomic hydrogen formation;
- stress state of the pipeline along the route. The higher the tensile (mechanical) stresses, the greater the penetration capacity of hydrogen into the metal at locations where the insulation is broken;
- distribution of “pipe-ground” potential difference along the pipeline. The larger the pipe-to-ground potential difference, the higher the intensity of atomic hydrogen formation at the points of insulation failure;
- degree of brittleness of pipeline metal in places of insulation coating failure (checked during well inspection). An increase in embrittlement is one of the signs of metal saturation with atomic hydrogen;
- soil corrosive activity. The lower the specific electrical resistance of the soil, the higher the concentration of hydrogen ions in the groundwater, therefore, the more intense the atomic hydrogen will be released at the places of insulation failure.

During crack growth, nondestructive testing methods are limited to detecting defective (metal) pipe sections and measuring crack sizes.

2.2. Methods of insulation coating control (without opening).
There are three methods to control the insulation coating without opening the pipe (without corrosion):
- magnetic location method based on the analysis of magnetic fields created around the pipeline;
- methods and devices based on the measurement of electrical currents in the pipeline;
- methods and devices based on the measurement of potentials in the pipeline and above ground.

The latter, using a powerful mathematical apparatus implemented in Orion series tool complexes, is most suitable for inspecting gas pipelines susceptible to stress corrosion. It allows simultaneously determining not only insulation defects, but also the integral transient resistance of the insulation shell (without opening the pipeline), as well as abnormally stressed zones, measuring all current characteristics, including currents of the electrochemical protection system and various types of interference.

2.3. Methods of stress control (without opening).
Overloaded sections of the pipeline introduce certain distortions into the magnetic field around the pipeline. All existing methods and devices for detecting areas with increased stress (without opening) are based on this phenomenon.

There are several devices that allow controlling the stress state of pipelines without opening them, and all of them have common drawbacks: difficulty of interpreting the results. Orion series complexes using the magnetic localization method are the most effective among them.

2.4. Methods for estimation of pipe metal embrittlement.
Pipe opening is required to evaluate pipeline metal properties. The methods for measuring hardness, as well as some magnetic properties (coercive force), can be used to monitor the state of the metal of operating pipelines. But all methods are very approximate, so for this during further accidents and repair work it is better to use metal cut from pipelines and conduct tests in laboratory conditions.

2.5. Methods of pipeline control at crack growth stage.
The development of cracks during stress corrosion cracking can be monitored based on the results of periodic inspections of gas pipelines using linear diagnostic methods. Tubular flaw detectors shall be magnetic with longitudinal and transverse magnetization and have such accuracy that they can reliably detect external cracks with an accuracy of not less than 10% of the wall thickness. For additional control of detected cracks, it is necessary to open the pipeline and conduct a well study using contact diagnostic methods: ultrasound, magnetic powder, magnetic noise and others (at the discretion of specialists and experts).
3. Results and Discussion

3.1. Comprehensive analysis of stress corrosion diagnostics.
Considering that the development of stress corrosion cracking occurs when several conditions are combined, it is necessary to collect all the measurement results obtained by different methods and at different times in one database. To do this, there is a need to introduce a single coordinate system. In modern conditions, the GPS global positioning system (or the Russian analogue Glonas) is the most suitable for this.

Precise quantitative criteria for the risk of developing stress corrosion have not yet been developed, so an expert approach is recommended. A scoring system is sometimes used to formalize this method as much as possible.

Areas where the following two conditions are met simultaneously are potentially hazardous:
1) soil water or moisture has access to the metal surface (there are defects in insulation, there is no adhesion);
2) at least one of the components of the stress state is at least 0.5 of the metal yield strength.

The risk of stress corrosion increases if the following additional features are present in the area (individually or simultaneously):
- site is located 30 km from the operating compressor station;
- pipeline metal has signs of embrittlement;
- soil is very aggressive;
- corrosion defects detected during smart pigging;
- integral transition resistance of insulation in this section is less than 500 Ohm-m²;
- pipeline ruptures previously occurred within 5 km of this section;
- cracks were found within 5 km from this area during the inspection of the quarry.

A section of a gas pipeline shall be considered to be subject to stress corrosion cracking if:
- at least one stress corrosion accident occurred;
- at least one stress corrosion crack was detected during trench inspection;
- stress defects were detected based on the results of in smart pigging.

The pipeline should be considered at risk of stress corrosion if it has been found that in one of the other gas pipelines in the region with similar characteristics and under similar conditions, stress corrosion cracking occurs.

Based on the correct development of stress corrosion cracking, it is recommended to establish the following frequency of inspections of a pipeline subject to stress corrosion cracking:
- diagnostics by magnetic position (control of insulation coating, stress state, aggressiveness of soil) – 5-7 years;
- in-line inspection – 5-7 years;
- electrometric measurements (electrochemical protection) – 2 times a year;
- works in the field of industrial safety – 10 years;
- study based on the results of online diagnostics and magnetic location.

3.2. Prerequisites for calculations.
All calculations begin with setting the task and the source data. In case of evaluating the stress corrosion in gas main pipelines, the tasks were formulated as follows:
- to determine the strength of pipeline sections with corrosion cracks (allowable working pressure);
- to determine the residual life of these sections for the specified mode of operation (dependence of the residual life on the operating pressure).

The following sources shall be used to configure the source data:
- design documentation and gas pipeline passport (diameter, wall thickness, steel grade, pipe type, design pressure);
- as-built documentation (welding technology, weld joint quality control data, insulation coating type, commissioning time, acceptance test data);
- operational documentation (climatic and geotechnical conditions, allowable operating pressure, actual operating pressures and temperatures, pressure and temperature cycles, external loads, information on failures, repair works);
3.3. Evaluation of the service life of a pipeline section subject to stress corrosion.

When determining the residual life of the main pipeline subject to stress corrosion, the following must be taken into account:

- as noted above, the development of stress corrosion includes two stages: incubation period and crack development period. The transition from the incubation period to the crack growth period is almost always unknown. It depends on a variety of uncontrollable factors. Therefore, it is silly and dangerous to rely on the assessment of this moment for practical use;
- according to SNiP (construction rules and regulations), cracks on the main gas pipelines are considered an unacceptable defect. This is a fully justified position, since many factors with unknown characteristics also affect the growth rate of cracks. Therefore, from the point of view of safety, it will be correct not to wait for cracks to grow to a critical level, but to eliminate them as they are detected;
- the diagnostic methods of the main gas pipelines are not sufficiently developed to make sufficiently accurate predictive estimates on their basis, especially for the life of areas subject to stress corrosion. The fact that smart pigging did not reveal stress corrosion defects does not in any way mean that there are no such defects. Therefore, it is necessary to assume that there are defects, especially in those gas pipelines which service life has exceeded 20 years.

Based on the developed physical model of corrosion cracking of main gas pipelines, the most effective control methods are systematized and proposed during incubation of development and cracking. It was found that one of the most advanced methods of controlling gas pipelines susceptible to stress corrosion cracking is a magnetic location method.

Stress corrosion is a very dangerous type of damage to parts and equipment in chemical, gas-oil and processing, metallurgical, energy (heat, hydro and nuclear power plants), shipbuilding and other industries. During the development of this process, there is usually brittle destruction of the metal without noticeable plastic deformation.

Corrosion cracking of steels of various chemical composition, structure and strength can occur in alkaline, nitrate and chloride solutions, in solutions containing hydrogen sulfide, ammonia, hydrogen cyanide, carbon dioxide and chlorine iron, in aqueous HNO₃ solutions, in thin moisture films, especially in the presence of an oxidizing agent. The list of media capable of causing the corrosion of metals and alloys has not yet been exhausted. The risk of corrosion cracking is that in the absence of visible changes, non-predictable instantaneous destruction of metal materials may occur in a short time.

3.4. Initial prerequisites for calculation.

All calculations begin with setting the task and the source data. In case of evaluating the stress corrosion in gas main pipelines, the tasks were formulated as follows:

1) to determine the residual life of these sections for a given mode of operation (dependence of the residual life on the operating pressure);
2) to determine the pipeline sections strength, where corrosion cracks occur (allowable working pressure).

The following sources shall be used to define the source data:

- design documentation and air duct passport (diameter, wall thickness, steel grade, pipe type, design pressure);
- as-built documentation (welding technology, weld joint quality control data, insulation coating type, start-up time, acceptance test data);
- operational documentation (climatic and geotechnical conditions, allowable operating pressure, actual operating pressures and temperatures, pressure and temperature cycles, external loads, information on errors, repairs);
- reports on diagnostic studies, including smart pigging, magnetic location, electrometric measurements, well surveys;
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- reports on diagnostic studies, including smart pigging, magnetic location, electrometric measurements, well surveys;
- expert opinions for the last 10 years on this gas pipeline and accidents that occurred on its section;
- pipe sections cut from the pipeline during repair works;
- results of metal pipelines testing in laboratory conditions.

As noted above, stress corrosion has two stages of development. The first is the incubation period, which is accompanied by the generation of atomic hydrogen on the surface of the pipeline metal, the penetration of hydrogen into the metal and microstructural transformations in the metal. Due to these phenomena, the metal of the pipeline reduces ductility (becomes brittle), internal stresses in the metal increase, and microcracks are formed and accumulated in the metal structure.

The intensity of processes during the incubation period is determined by two main factors:
1) stress level in pipe wall at atomic hydrogen extraction section.
2) intensity of atomic hydrogen generation on the metal surface.

According to these factors, there are two ways to suppress stress corrosion of existing gas pipelines during the incubation period:
1) reduction of stresses in the pipeline wall in problem sections (in places where atomic hydrogen release is not stopped for any reason);
2) suppression of atomic hydrogen generation on the pipe metal surface.

In order to successfully combat stress corrosion on gas main pipelines, it is important to choose the insulation coating correctly. An example of a wrong choice is shown in the figure.

![Fig. 1. State of film insulation of gas pipeline (a) and pipeline surface under insulation (b); (light bands – areas accessible for groundwater; dark areas – primer remains on the pipeline surface)](image_url)
4. Conclusion
The following observations can be made based on the inspection of gas pipelines in areas subject to stress corrosion:
- film has many undulations, mainly in the region of 3-9 hours of the pipeline cross-section;
- almost all stress-corrosion cracking accidents occurred on pipelines covered with insulation film applied in the field;
- water, salts and corrosion products accumulate under the film;
- there are cavities (“pockets”) along the welds;
- there is almost no adhesion of the insulation coating.

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