Corrosion cracking under main pipelines stress

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Abstract: Stress corrosion cracking (SCC) or stress corrosion is one of the most dangerous types of damage in chemical, oil and gas industry, as well as in processing, nuclear, heat and power, metallurgical, shipbuilding and other industries. Corrosion cracking of pipelines under stress (stress corrosion) is the main source of emergency incidents (emergencies) mainly in gas main pipelines. This type of corrosion is widely known and very dangerous.

1. Introduction

Many countries in the world, especially Russia, the USA, Canada and the countries of the European Union producing and transporting natural gas face serious difficulties associated with the stress-corrosion destruction of gas pipelines. Currently, more than 50% of damage is recorded on gas main pipelines due to stress corrosion cracking. Thus, this damage is causing global economic and environmental losses. In addition to direct and indirect economic damage, accidents on gas pipelines cause huge environmental losses and are associated with a threat to human life. These forces enterprises working in gas transportation and guaranteeing the reliable operation of pipelines to create and implement modern stress corrosion monitoring systems, which is impossible without a general scientific study of this phenomenon.

2. Methods and Materials

The confidence and safety of oil and gas pipeline systems is particularly important on the nationwide scale. But, as practice indicates, there are some issues in this area. The more acute difficulty is associated with stress corrosion of gas main pipelines, which is a prerequisite for most emergency situations.

In case of stress corrosion the alloy of gas pipelines is unevenly embrittled and cracked, almost always starting from the outer surface. In some areas the depth of cracks over 20-25 years of operation reaches 50% of the wall thickness, which, in fact, leads to the exhaustion of all strength properties provided for by generally recognized brands and plans. This then leads to a pipe failure, gas release under huge pressure, self-ignition with a height of fire up to several dozens of meters. During pipe failure its pieces are thrown out at large distances from the destruction space; the ground plane is burned at times up to 100 m or more from the center of destruction. As we see, the stress corrosion of gas pipelines is a great threat both for the pipelines themselves and for the environment and residents [1-4].
Despite the significance of this difficulty, no productive ways have been developed to combat stress corrosion.

To date, the issue is addressed through the following three steps:

1) smart pigging, which reveals failures (stress-corrosive and others) with a depth of more than 0.1...0.2 of the wall thickness depending on the accuracy of flaw detection devices;

2) calculation methods, which are used to assess the threat of identified failures and residual life of the pipeline section;

3) pipeline repair by replacing sections containing critical failures.

This allows reducing the possibility of pipeline rapture, but contains important defects.

First, the correctness and reliability of smart pigging results are low in relation to stress-corrosion defects, and the validity of stress-corrosion has not been studied to the desired degree. Therefore, the inaccuracy of assessments and monitoring is high. Each time there is a possibility of unexpected destruction, which is in fact found in practice.

Second, the smallest failures are not established. Their number is much larger, and they will continue to grow, including the subsequent removal of all safe failures. That is, with the presented layout, the formation of stress corrosion does not stop.

Third, the position of the pipeline during the incubation period of stress corrosion formation is not diagnosed. As a result of the study, at the moment the number of new and old stress-corrosion failures will be even more than in the previous period. This strongly requires a continuous increase in the volume of repair cases.

The mechanism of stress corrosion development differs from the mechanisms of development of other types of corrosion. In fact, the study of a large number of failures showed that stress corrosion is affected by factors that are in no way related to each other at first glance. This leads to various conclusions and proposals. Some experts propose to create special grades of steels for gas pipelines, others – to create more effective insulation materials, and the third – to transform the technology of pipeline construction. There are also recommendations to treat the soil along the entire main pipeline with special compositions. But none of these recommendations fully solves the problem of stress corrosion in general, because they “extract” only one or a certain number of random components from an absolute range of factors and dependencies [2]. Studying the destruction of the main pipeline laid in various natural climatic criteria, operated under different modes, which were influenced by various factors, experts came to completely different results and made conflicting conclusions. Specialists themselves also have different skills, education, and adherence to different opinions (human factor) [5].

Until now, generally accepted mechanisms of stress corrosion on the main pipeline have not been established, and methods of protection have not been developed. At the same time, the very physical nature of the phenomenon remains unclear. Without establishing such a physical (chemical, mechanical) model, it is difficult to expect success in the fight against stress corrosion [6, 7].

The model is intended to describe all known facts and answer several questions, including:

- Why is stress corrosion often observed on the main gas pipelines and practically not found on main oil pipelines, on gas supply pipelines, on field pipelines?

- What is the meaning of the insulation coating (bitumen, film, yard coated)? What properties need to be expanded to more effectively inhibit stress corrosion?

- How does the electrochemical protection affect stress corrosion?

Only after obtaining the corresponding physical model of the present phenomenon and testing it on all known facts can we hope for significant results in solving the problem of protecting gas pipelines, especially those that are created from pipes without yard coated insulation and have been in operation for more than 20 years.

In the world, stress corrosion was first encountered more than a hundred years ago during the construction and operation of large-capacity ships. At that time, the cause was associated with exposure to seawater [8].

Following this, stress corrosion affected the power parts of nuclear power plants. At the same time, the cause was associated with the effect of radiation on structural foundations.

After that, stress corrosion manifested itself and more and more often occurred at thermal power plants. Here, the reason was associated with the effect on the metal of overheated water vapor [9].
In chemical industry stress corrosion was found on pressure vessels with hydrogen. This information gave impetus to the study of the interaction of metals with hydrogen. This resulted in the teachings of metal hydrogenation, hydrogen embrittlement and cracking.

As soon as stress corrosion began to occur on main gas pipelines (in international practice – in the 60s, in Russia – in the 80s), various experts associated this with various reasons: climatic criteria, terrain, temperature, vibration, soil structure, including biological composition of the earth. One of the most important unresolved issues was the cause of stress corrosion on main gas pipelines and why it does not happen on oil pipelines, however all the initial foundations (metal, pipes, insulation), generally recognized design measures, climatic and ground conditions are absolutely the same? This question led many experts to decide that the cause of stress corrosion lies in pumped raw materials – natural gas. But here there was a different question – why does stress corrosion not occur on gas pipelines of the gas distribution system, while the pumping raw materials are the same – natural gas?

Having found no answers to these ordinary questions they decided that the mechanisms of stress corrosion of gas pipelines are quite complex, literally cannot be deciphered, and to some extent they agreed with the presence of the appearance of “inevitable evil” [10, 11].

Having failed to suspend or at least slow down the process of stress corrosion, they decided to fight at least the consequences – to timely eliminate defects that increased to serious volumes. In other words, this cannot be accepted as ideal, because the mechanism itself, which leads to the occurrence and development of defects – stress-corrosive pits, is not suspended. The study of the presented problem has not yet revealed the causes and mechanisms of stress corrosion control [12, 14].

All the above shows that it is important to study the presented phenomenon and build a physical model. Just with the emergence of such a model, it is possible to hope for success in combating this phenomenon.

3. Results

The idea of stress corrosion mechanisms should be set on the basis of a consistent chain of reasoning around two main issues.

The first main question: Why does stress corrosion happen on gas pipelines, and on other pipelines (oil product pipelines, gas distribution system, oil pipelines, field pipelines) stress corrosion does not occur? What is the peculiarity of the main gas pipelines?

As the standard study demonstrates, main gas pipelines (in the territory of areas where stress corrosion is found) have huge diameters and are used under large working pressures. All this is explained by the fact that the mechanical stresses in the walls of the main gas pipelines are significantly higher than in all other pipelines. This is the key difference between the main gas pipelines and all other main pipelines.

Circular (circumferential) stresses on straight sections of pipelines under the action of the working pressure are approximately twice as much as axial stresses. This explains the case that most of the stress corrosion cracks detected are directed longitudinally (perpendicular to the circumferential stresses that are most important).

Significant bending stresses in the longitudinal direction occur in sections of pipelines along the main pipeline with complex geodynamic zones, in which there are sections of elastic bending. The larger the pipe diameter and the smaller the bend radius, the higher the bending stresses under other general conditions. This explains the case that stress-corrosion cracks occur in these areas of the main pipelines in the circumferential direction (perpendicular to the longitudinal stresses that are critical in these areas).

Thus, the presence of large tensile stresses in the pipeline wall is considered one of the points determining the conditions for the development of stress corrosion. Most likely, the stress corrosion occurs quicker if the stress is closer to the point of metal flow. This is the second conclusion is the study of this phenomenon – stress corrosion cracking.

As a result, a second conclusion is imposed that metals in some way have some kind of stress corrosion limit, similar to the fatigue limit. It is likely that the metal fatigue limit is absolutely identical with the stress corrosion limit. If the stress is below the fatigue limit, then no fatigue break occurs, for example, the stress corrosion also does not occur if the stress in the pipe wall is not above the stress corrosion limit.
Why does stress corrosion appear on the outer plane of the gas pipeline?

In fact, the study of metal in the field of stress corrosion destruction demonstrates that the metal of the pipe wall turned out to be embrittled and cracked from the outer surface. The metal is held in a flexible position generally on the inner surface side. In this study, it is possible to verify the results of mechanical tests of samples (Fig. 1). Cracks on the surface of samples were not visible prior to testing. They were seen on the outer surface during tensile testing.

![Sample of metal stress corrosion after tensile testing (external wall)](image1)

**Fig. 1.** Sample of metal stress corrosion after tensile testing (external wall)

In case where stress corrosion was oriented only by the degree of mechanical forces, which are similar in volume to the pipe wall, embrittlement and cracking would occur equally actively throughout the pipe wall. Here, when stress corrosion occurs on the side of the outer surface, it is possible to state that a certain special process occurs on the outer surface of the pipe, and stress corrosion is considered only a consequence of this process.

Stress corrosion occurs only in underground pipeline sections; no cases of stress corrosion were detected in air segments. In sections where stress corrosion is found, an insulation coating of unsatisfactory quality is always found: at times adhesion is absent, embrittled and cracked, ground water accumulates under the insulation (Fig. 2-5).

Based on the fact that the metal is embrittled, the idea arises that some elements (molecules, atoms, something else) from the outside surface fall into the metal and prevent dislocation (of course, the flexibility of metals is guaranteed by the mobility of dislocations). Other components (nitrogen, carbon, hydrogen, etc.) can enter the metal only at high temperatures. At normal temperatures, at which the pipeline is operated, there is no chance for molecules to get into the metal.

![Insulation coating wrinkling](image2)

**Fig. 2.** Insulation coating wrinkling
Fig. 3. Pipeline surface after removal of the insulation film (light strips – sections where there was contact of metal with ground water; dark areas – primer remains on the pipe surface)

Fig. 4. Embrittlement and cracking of insulation coating

Fig. 5. Loss of adhesion under insulation

Elementary particles, such as protons, neutrons, a-particles and others are exposed to this phenomenon. But there are a large number of these particles, and they are present everywhere as the radiation background, and stress corrosion does not happen everywhere. Thus, it is necessary to find the key origin of elementary particles on the outer surface of underground main pipelines (the presented image of stress corrosion occurs in underground sections of the main pipelines). There is a solution, and it is related to electrochemical protection of pipelines.
Naturally, underground pipelines are under double corrosion protection: insulation coating and electrochemical protection. The electrochemical protection of the pipeline is that in relation to the ground, the main pipeline is supported by an electric field potential from -3 to -1 V. It is believed that this suspends the oxidation of the metal in the part where the insulation coating is damaged. But in fact the situation is somewhat different.

Most main pipelines contain film insulation applied in the field. When the main pipeline is coated and filled the insulation coating in the trench comes down together with the soil and creates a large number of folds on the lower part of the half surface. Besides, at a minimum time, the cling layer loses adhesive qualities and the film is separated from the pipeline surface. Thus, the insulation coating is converted into a capsule, from the inside of which a pipeline is located, and ground water is located between the pipe and the capsule. This causes a change in the electric field in the circumference of the pipe metal, which reduces the protective effect of electrochemical protection.

Groundwater contains a large number of different particles (ions), among which are positively charged hydrogen cations (H\(^+\)), which are surrounded by polar water molecules \(\text{H}_2\text{O}\) (hydroxonium ion \(\text{H}_3\text{O}^+\)). Hydroxonium ions (\(\text{H}_3\text{O}^+\)) have a single positive charge, because of this they are attracted to the negatively charged surface of the pipe. There, the positive hydrogen cation is neutralized in the electronic metal field, released from its own environment. At the same time, the electron of the hydrogen atom alone, being valent, continues to enter the electron shell of the metal, and the preserved nucleus is represented by some elementary particle, like a proton. Further, this proton (elementary particle) is able to simply penetrate into the metal (negatively charged), maintain greater mobility there for a long time and as a result create other factions there with new substances. Most possible factions are those with the atoms of hydrogen, oxygen, carbon. All these factions lead to the deformation of the crystal lattice of the metal, which after that inhibits the movement of dislocations. Thus, dislocations are slowed down. Lowering the dislocation movement causes a decrease in metal flexibility, namely metal embrittlement. Moreover, an increase in the concentration of proton in the metal leads to an increase in internal stress. In turn, internal stresses add up with external stresses, and such formations lead to pipeline cracking.

Other components (with the exception of hydrogen \(\text{H}_2\)) are not able to lead to metal embrittlement, because none of them when a valence electron is lost turns out to be an elementary particle that can penetrate the metal at normal temperature. Hence, the presence of an atomic hydrogen source on the metal plane of the pipes is considered the next necessary condition for the development of stress corrosion.

In addition to the considered source (groundwater + electrochemical protection with shabby insulation), there may be other sources of atomic hydrogen, for example, gas or nutritional products of microorganisms (biocorrosion).

Thus, the mechanism of stress corrosion in its own formation consists of several stages:
1) Incubation period is conjugated with the penetration of hydrogen atoms into the depth of the metal;
2) Occurrence of microcracks, subsequent accumulation of gases, combination of microcracks, increase of cracks up to volumes observed by diagnostic methods;
3) Crack formation happens due to the effect of internal and external forces;
4) Destruction of the main gas pipeline.

At the moment, there are views that multiple conditions affect this type of corrosion: chemical structure, soil moisture, atmospheric conditions, acidity, thermal interval, vibrations, preserved stress in the main pipeline, stresses of multiple forms of loads, location of a relatively compression station, landscape of the territory, steel brand, presence of some microorganisms in the soil, etc. In fact, all this is possible. All these conditions will not be able to start the stress-corrosion mechanism on their own, but can only increase or reduce the influence of the main conditions: hydrogen and stress.

External factors influence the speed of the first stage of the process – the release of atomic hydrogen on the metal plane. The external factors include the state of the insulation coating (scrap, lack of adhesion), potential difference between the pipe and the soil, state of the metal plane, chemical composition and the concentration of elements in the ground water, pH of the medium (acidity), humidity, pulsations, atmospheric conditions, landscape of the territory, temperature change of the external medium (soil).
The speed of the second and third stages of the process – the penetration of hydrogen atoms into the depth of the metal and the processes inside the metal, are greatly influenced by internal factors. The internal factors include structural features and the chemical composition of the alloy (metal), temperature of the alloy, mechanical stress, and the nature of the treatment. At the same time, ring stresses from working standard pressure and external factors, as well as internal factors, among which there are those that affect the crystal lattice and dislocations, are particularly important.

As we see, certain conditions, for example, pulsation and temperature belong to both external and internal factors, since they affect all processes that occur both outside and inside the metal.

4. Conclusion
Unlike other types of corrosion, metal stress corrosion may occur and appear not only on the surface, but also from the inside of the metal.

From this hypothesis follows a very significant conclusion that may be considered the main one in the protection of gas pipelines from stress corrosion. The conclusion is that if the occurrence of atomic hydrogen on the metal surface is eliminated, then all other processes leading to the phenomenon of stress corrosion will slow down. Since for these processes there will also be no single main accomplice of the process – hydrogen (similar to the fact that if oxygen is removed, oxidation will not occur).

The present assumption is not yet considered a physical model of stress corrosion, but claims to be it in accordance with the results of additional studies depending on the established tasks.

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