Failure Monitoring and Asset Condition Assessment in Gas Supply Systems

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Abstract: The urgent task is assessment of the emergency danger of damage to overhead and underground gas pipelines, depending on conditions of their laying, the nature of damage, gas pressures, diameters, atmospheric impact, as well as assessment of the environmental impacts of the gas leaks from damaged gas pipelines. Despite equipment and technologies improvement, the safety factor of the gas supply systems remains a priority. The purpose of this study to investigate issues of technological and functional reliability of the gas distribution systems. Development methodological principles for efficiency increase and reliability of the gas distribution systems by narrowing zone of economic uncertainty and establishment communication between reliability indicators and design features of the gas supply systems. Methods of the system analysis are used. The research is based on generalization and systematization of materials of the gas distribution organizations for gasification the territory of the Russian Federation. There is the analysis of statistical data on accident rate at the objects of the gas industry during the period from 2010 to 2016. Calculation of the number and specifics of the accidents occurrence is carried out on the basis of a system analysis of the gas supply systems elements.

1. Introduction

In operation process distributive gas networks are exposed to a wide range of tension and impacts that, in combination with a long operation period, leads to decrease of reliability level. Material on condition of accident rate in gas economy allows to reveal weak fields in the safety system, to develop the program of actions both as organizational plan and as to conduct analytical, pilot research and design developments [1, 2]. One of the most efficient, at the same time requiring considerable capital investments, ways to improve reliability of the gas supply systems is the replacement and reconstruction of morally and physically obsolete pipelines and elements of the gas systems [3]. The problem of ensuring reliable operation of the gas pipelines comes down to the solution of two main objectives: timely detection of defects and forecasting conditions for their development up to the point of destruction [3, 4, 5].

The most cost-efficient way of delivering natural gas to the final user is pipeline transport. However, this kind of hydrocarbon transfer is always accompanied by some transportation losses of the product. These losses, undoubtly, can be referred to the category of inevitable losses, this amount can be calculated and taken into account [3, 6, 7].
However, there are such gas losses, which are difficult to calculate and predict. These are the losses that occur in emergency situations with uncontrolled gas release into the environment and unauthorized cut-in during gas theft. Unauthorized cut-in causes heavy losses, connected both with the loss of the gas and carrying out recovery work on the emergency site, as well as with environmental consequences in case of low-quality construction of the cut-in. Therefore, there is a task to provide safety of the pipeline gas transport while design or reconstruction stage [3].

The main requirement for gas facilities are: ensuring reliable, safe and efficient operation of the gas supply system in economic and environmental terms.

One of the basic purposes of the gas supply systems is uninterrupted supply of estimated gas consumption to consumers. In this regard the specified parameter acts as a key high-quality indicator of the gas distribution system.

Distinctive feature of the gas networks is the duration of their operation, but longevity does not characterize reliability of the gas distribution system, it only assesses reliability of its constituent elements. In addition, feature of the gas supply systems is the social character. Accidents and incidents, besides economic and property damage, cause also moral damage to consumers and it is not possible to consider consequences beforehand [7, 8]. Due to low capacity storage of the low-pressure gas pipelines which is the reason of rigid communication between amount of the released gas from the network and amount of the consumed gas, it is not possible to increase reliability of such network at the expense of its capacity. This implies another difference between low-pressure gas distribution networks - a limited possibility of reservation, while the last one is one of the ways to improve reliability. At the same time, it should be noted advantage of the high-pressure systems, which storage is more than 50% higher than useful capacity of medium-pressure gas pipelines [2].

2. Results and Discussion

Data analysis on accident rate in the gas, gas-processing industry, objects of the main transport and gas storage and also gas pipelines operation, gas control facilities (installations), household objects and domestic gas equipment, presented on the website of the Rostekhnadzor [4], became an object of the research. Results of the analysis are presented on charts (Figure 1, Figure 2).

![Figure 1. An analysis of accidents at gas industry facilities.](image-url)
It is known that gas pipeline operation eventually leads to various defects formation: wall thinning, cracks, through defects [9]. There are number of factors that have negative effect on a physical condition of the gas pipelines including negative anthropogenic and natural impacts. It has an impact both on the frequency of accidents and total period of the gas pipeline operation [10, 11].

All emergency situations can be conditionally divided into the following groups: natural phenomena; design errors; mechanical damage; violation of construction and installation process.

In addition to these factors, use of the gas appliances, equipment and fittings with expired service life causes emergency situations. The Government of the Russian Federation adopted the Rules for the gas usage in terms of ensuring safety while usage and maintaining domestic and intra-apartment gas equipment in the provision of public utility services for the gas supply in 2013 (Enactment № 410, May 14, 2013), it requires provision technical diagnostics of the gas appliances and equipment with the expired service life, which, however, does not guarantee the extension of its use. In addition, an old equipment is the subject to annual maintenance, which increases monetary strain on consumers, and therefore, it is more expedient to make timely replacement of the gas appliances, equipment and fittings with expired service life.

Since December 2014 "The rule of industrial safety of hazardous production facilities which use the equipment working under excessive pressure ", approved by the Rostekhnadzor order from 25.03.2014 №116 come into the effect. These rules establish mandatory requirements to the organizations whose field of activity includes operation of the gas supply systems, aimed not only at providing industrial safety, but also prevention of accidents, incidents, operational injuries on hazardous production facilities and preparation of "The declaration of industrial safety of hazardous production facility" with the analysis, risk assessment and danger identification.

As the analysis showed, in 2016 there were 21 accidents at gas distribution and gas consumption facilities, that is 36% lower in comparison with the same period in 2015, while the number of fatal injuries decreased by 25% and all of them the result of gas suffocation [4]. 70% of the total number of accidents was related to the following causes: mechanical damage of gas pipelines during excavation works, mechanical damage to gas pipelines by road, the damage resulting from natural phenomena, corrosive damage to external gas pipelines, the breaks in welded joints, gas leakage at gas pressure reduction points, malfunction of boiler equipment, malfunction of liquefied petroleum gas equipment, other.
accidents are connected with mechanical and corrosive damage of the gas pipelines. The number of accidents related to equipment malfunction, gas leaks and explosions during ignition of gas-using facilities has decreased. 9% of the total number of accidents occurred due to faults in the equipment of the liquefied hydrocarbon gases. In the analysis, a large percentage of accidents from mechanical damage attracts attention, which demonstrates lack of proper control over the excavation production by various organizations.

Besides the assessment emergency danger of damages of the gas pipelines depending on the nature of laying, type of damages, pressure of the pumped-over gas, diameters of the gas pipelines, the relevant task is assessment of the environment impacts of gas leak from the damaged gas pipelines [3].

The amount of leakage depends on two main factors:
- the size of the damage (leakage) through which leak occurs;
- the category of the gas pipeline according to pressure.

The deterioration of fixed assets by the linear part of the gas pipelines is about 57% today. As a rule, most of the defects are caused by corrosion and mechanical damage, which is much more difficult to identify due its inaccessibility. However, with the use of modern measuring equipment, this problem can be successfully solved.

According to statistics, the amount of leakage due to emergency gas release because of gas pipeline rupture varies from 2,5 to 3 million m$^3$.

Using the mass conservation law, it is possible to determine the amount of gas emissions through the damaged part of the gas pipeline. Thus, for low-pressure gas pipelines, the amount of leakage, depending on the size of the damage, can be determined by a joint solution of the system of equations:

$$\begin{align*}
P_{s,l} &= P_1 - 54.5 \left( \frac{0.01}{d} + 2.9 \cdot 10^{-2} \frac{d}{Q_s} \right)^{0.25} \cdot Q_s^{2} \cdot l, \\
V_{s,l} &= 3.7 \cdot f_s \cdot P_5^{0.5} = 2.9 d^2 \cdot \phi \cdot P_5^{0.5} \cdot c_2
\end{align*}$$

(1)

$$\begin{align*}
P_{s,h(m)} &= P_1 - 1.11 \cdot 10^{-3} \left( \frac{0.01}{d} + 2.9 \cdot 10^{-2} \frac{d}{Q_s} \right)^{0.25} \cdot Q_s^{2} \cdot l, \\
V_{s,h(m)} &= 1090 \cdot f_s \cdot P_5
\end{align*}$$

(2)

where: $P_l$ - excess pressure in front of the hole of the gas pipeline damage, respectively for low ($P_{s,l}$), high and medium ($P_{s,h(m)}$) pressure gas pipelines (MPa); $P_1$ - absolute gas pressure at the beginning of the gas pipeline, (MPa); $d$ - internal diameter of the gas pipeline, mm; $Q_s$ - amount of the gas ejected to the site of damage to the gas pipeline; $l$ - estimated length of the gas pipeline of constant diameter, (m); $V_s$ - amount of the gas emission (leakage) into the atmosphere, (m$^3$); $f_s$ - area of the hole of the gas pipeline damage, (cm$^2$); $c_s$ - size of the damage (can be defined as the proportion of the total open cross-section of the pipeline).

As the analysis shows, the possible amount of leakage for domestic gas pipelines, depending on the size of the damage, can be $0.1\div1000$ m$^3$·h$^{-1}$ and for the external gas networks - $1000\div10,000$ m$^3$·h$^{-1}$. However, leaks from domestic gas distribution systems are more dangerous than gas emissions from external distribution pipelines. This circumstance is explained by the difficulty with creating conditions for the explosion of a gas-air mixture in open space without ignition source, while a leak inside the building can form an explosive concentration, leading to explosion and destruction [3, 12].

Explosion of the natural gas can happen at casual coincidence of the next events: failure in the reduction system, failure of the safety-fault and safety-shut-off valves and accidental source occurrence of ignition of the gas-air mixture. Effective safety measures are proper operation of the supply and exhaust ventilation and the equipment of the systems of internal gas supply with gas contamination alarms, automatically disconnecting the gas supply in case of emergency situations.
Calculation results show that gas leakage from medium-pressure gas pipelines is almost three times higher than the leakage from low-pressure gas pipelines. However, pilot studies have shown that the duration of the accident on gas pipelines with smaller diameter is significantly reduced and operation of such systems is more economical and reliable. At the same time, strict requirements to the installation quality and testing of the gas pipelines with various pressures must be preserved and strictly executed [14, 15 and other].

To determine the volume of gas emissions from damaged high, medium and low pressure overground gas pipelines, it is possible to consider a hypothetical model of a gas pipeline having the same diameter \( d \) and the same gas flow rate \( Q \). Piezometric graphs for high (medium) and low pressures for accident-free mode and in the absence of gas consumption are shown in figure 3.

As follows from the review of the graphs, the amount of gas released into the atmosphere depends not only on the gas pressure inside the gas pipeline at the site of damage and the hole area, but also on the hydraulic regime [3].

The basic methodological principles and general requirements to calculation the probability of accidents and incidents occurrence at gas networks and risk analysis are presented in [3, 12, 14] and include: analysis and organization of work; hazard recognition; assessment of the risk, clarification of the objects included in the gas distribution system (as far as certain linear objects and/or their sections are dangerous), development of various recommendations on risk reduction based on this information.

Analysis of a large number of accidents on gas supply systems shows that the process of accidents occurrence has an accidental nature [16, 17, 18, 19]. The probability of an accident on the gas pipeline under the same conditions of installation and operation can be considered the same, although in actual practice some part of the gas supply system will be in more favorable conditions. For example, comparison gravity of the consequences of an accident that occurred near a power source and peripheral areas. One of the important issues requiring the solution at design stage systems of the gas supply is the question of expedient number and installation locations for the disconnecting devices, which should be guided by considerations of reliability and economy. Obviously, an unreasonably
A large number of disconnecting fittings increases the cost of the system and complicates operation. However, the extension of the cut-off area in the case of emergency has a significant impact on the continuity of the gas supply. For example, in medium-pressure ring networks, each section has the possibility of the gas supply from both sides and in case of an accident, gas supply would be shut off to consumers located only in the emergency area or consumers will be able to receive gas bypassing the reserve capacity of neighboring serviceable network sections. Therefore, in order to increase the reliability of such a network, disconnecting devices should be installed on the condition that the gas fuel is supplied to as many consumers as possible in case of an accident and provide reserve capacity that minimizes unreasonable supply of the gas fuel in case of incidents and accidents [3, 20]. Thus, the accumulation and systematization of data depending on the nature of emergencies, the extent of damage to specific consumers can reveal the most vulnerable aspects and develop organizational measures for their prevention and elimination, including through various studies and design developments directed to increase level of security systems of gas distribution, minimization of material damages and human victims. Calculation of the optimal level of reliability, as one of the technical and economic categories, should be one of the necessary stages in the development of projects for the gas distribution and gas consumption systems and their further operation [3, 19].

3. Conclusions
- gas distribution system generates a stream of accidents and incidents, the intensity of accidents depends on consumption of the gas fuel, extension of the gas pipelines, expire period of the gas facilities, configuration system, gas pressure category and other determining factors [21];
- emergence and development of emergency situations is mostly random;
- the most dangerous object of the gas supply systems are domestic systems and gas-using equipment;
- origin of emergency situations has a regular nature due to violation of the regulatory documentation requirements and non-compliance with construction and installation work by exterior organizations [22];
- accidents caused by the presence of internal hidden defects of the gas-using equipment, fittings and pipelines are characterized by heavy consequences and have an uncontrolled nature.

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