

RISK ANALYSIS OF NATURAL GAS TRANSPORTATION PROCESSES

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Abstract. The problem of ensuring technological reliability and environmental friendliness of the natural gas transportation process, the main approaches to risk assessment and management at industrial facilities are considered. To increase the trouble-free operation of the gas transmission system, a comprehensive risk management system is proposed. The research of an ecological condition of the ground layer of air is being done in Bohorodchany district based on the constructed maps, which represent a distribution of harmful matters concentrations, its coefficients and also the coefficients of ecological danger and the map of a total contaminating index. The general chart of ecological risk is represented. Analysis of objects for gas transportation is made. The method of area detonating calculation and distance of mixture explosive cloud distribution is considered during the damage at the main gas pipeline. Area detonating calculations and the distance of mixture explosive cloud distribution are conducted at different wind speeds.

Keywords: gas transportation systems, main pipelines, ecological risk.

1. Introduction

Ukraine's gas transportation system is the second largest in Europe after Russia. It comprises a network of gas pipelines with a total length of over 38.5 thousand km (pipe diameter 1020–1420 mm), 73 compressor stations and 13 underground gas storages with an active gas volume of 32 billion m³. The inlet system capacity is 290 billion m³ of gas per year, and output is 176 billion m³ per year.

The pipeline system of Ukraine has received significant development in the Ivano-Frankivsk region. In particular, large main gas pipelines “Soyuz”, “Progress”, “Urengoy – Pomary – Uzhhorod”, “Ananyiv – Chernivtsi – Bohorodchany”, “Torzhok – Dolyna” and others have been laid. They transport gas on the territory of the region. The above-mentioned gas pipelines have a high level of wear, so there is a high risk of accidents.

One of the important gas transportation hubs in Prykarpattia is Bohorodchany. Nowadays, the oil and gas industry pays much attention to providing reliability and safety during the construction and operation of main pipelines. Despite this, the emergencies associated with gas transportation by pipelines occur very often (Peekema, 2013; Jo, Ahn, 2002; Mandryk et al., 2020). In general, such accidents include high material costs for the oil and gas pipeline operating companies and significant damage to the environment, people, and property in the vicinity of the emergency pipelines. Therefore, the decrease in the probability of emergencies on the main gas pipelines is one of the immediate issues in this field. The problem is especially important for pipelines that are located and operated in special climatic conditions. The main factors, which contribute to the emergency occurrence, are the use of significant amounts of flammable and explosive substances in operating procedures causing abrasion of equipment and pipelines; operating procedures under pressure; harsh climatic conditions and others.

Pre-accident analysis is an important aspect of gas transport ecological risk management. The main causes of gas pipelines accidents are pipeline corrosion (including internal and external), construction defects, mechanical damage (including excavation work), diversions, unauthorized junctions, third party's activity, operational imperfection, manufacturing defects of pipes and equipment, natural disasters (Grudz et al., 2020; Maruschak et al., 2016). During the transportation, the loss of piping integrity may occur, which would lead to the release of hazardous substances into the environment. The main result of such accidents is the transported gas leakage, which creates toxic pollution of the environment. Moreover, as a result of gas leakage evaporation, the cloud of the explosive mixture is formed. The presence of an ignition source within the cloud may lead to its inflammation and

explosion. The highest risk of accidents on pipelines is connected with longitudinal damages. They can occur during the formation of a corrosive gas pocket or guillotine ruptures both on the basic part of the pipe and in the zone of welding joints. Therefore, the loss of piping integrity is considered the most frequent initiating event, which causes the hazardous release of substances into the environment (Yavorskyi et al., 2017; Cruz, Krausmann, 2009). The loss of piping integrity mode influences the types of leakage. If the discharge area is small, a relatively longtime outflow through a hole is observed. On the other hand, if pipeline integrity damage is significant, considerable volumes of hazardous substances reach the environment immediately.

2. Methodology

Ecological risks have two important characteristics: damage and uncertainty. First, they have the potential to cause long-term and even irreversible damage to the eco-environment. In turn, this damage can affect the quality of life, not only for people but also for other living species. Second, they are stochastic, and possibly cumulative or synergistic, and often difficult to forecast.

A regional ERA is a branch of a general ERA. It considers the co-occurrence of both risk sources and risk receptors and provides an assessment of exposure and effects that takes into consideration their uncertainty and spatial heterogeneity. For this reason, the regional ERA is more complex than the general ERA (Fig. 1)

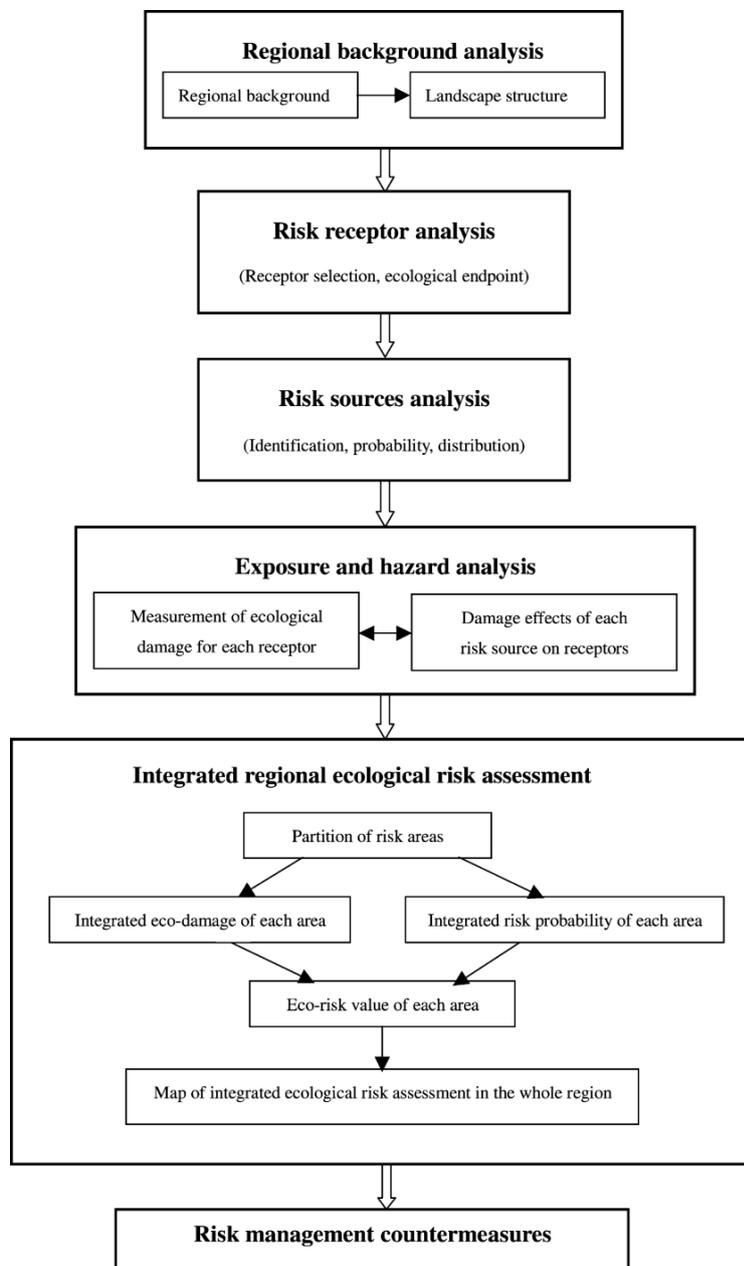


Fig. 1. Predictive analytics steps to be carried out in the pipeline system

A phenomenological approach is based on emergencies possibility determination using the analysis results that represent conditions connected with the laws of nature. This approach is the easiest one to use, and it gives reliable results if operating processes have a sufficient margin to limiting levels. However, it is unreliable when the abrupt change of substances or systems occurs. This approach is preferable to compare the safety margins of different potentially dangerous objects and is useless in the analysis of emergencies, which depends on the reliability of different parts of the object or its safety facilities. Fig. 2 shows the conceptual frame layout of dynamic risk assessment.

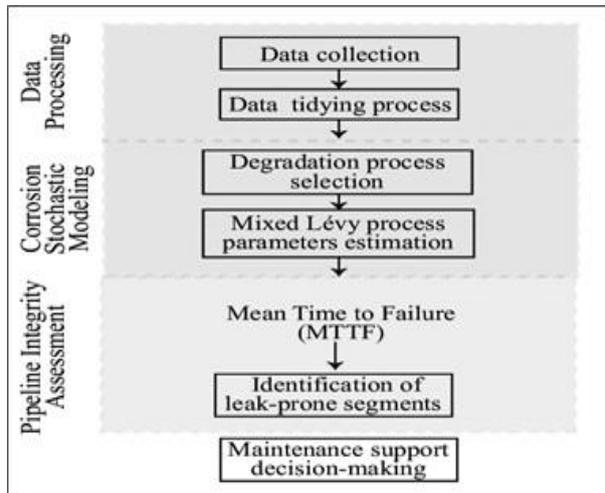


Fig. 2. Conceptual layout of dynamic risk assessment

The deterministic approach provides an analysis of the sequence of the accident development from the initial event through a series of suggested failures. The emergency process is studied and predicted with the help of mathematical modelling, construction of simulation models and complex calculations. Disadvantages of this approach include the gaps in some important events in accident development; difficulty in the adequate mathematical model construction; complexity and high cost of experimental studies to validate computer models. The expert approach is based on obtaining quantitative risk assessments by the processing of experts' opinions. The main disadvantage of this approach is the necessity to analyze the objectivity and reliability of experts' opinions. Fig. 2 describes the predictive analysis sequences to be done in the oil and gas pipeline industry.

The probabilistic approach involves the probability assessment of the accident. This approach allows analyzing the chain of events and equipment failures and estimating the total probability of the accident. The main disadvantage of this approach is related to the lack of statistics on equipment failure. In addition, the usage of

simplified design schemes reduces the reliability of the risk assessment for serious accidents. However, this approach currently is considered as one of the most perspective ones. In this paper, a probabilistic approach was used. Its application can be explained by the capacity to model all possible pipeline accident scenarios. Different techniques (statistical data, event tree analysis, fault tree analysis, etc.) allow us to identify and quantify all scenarios, as well as to determine the protective actions if an emergency occurs.

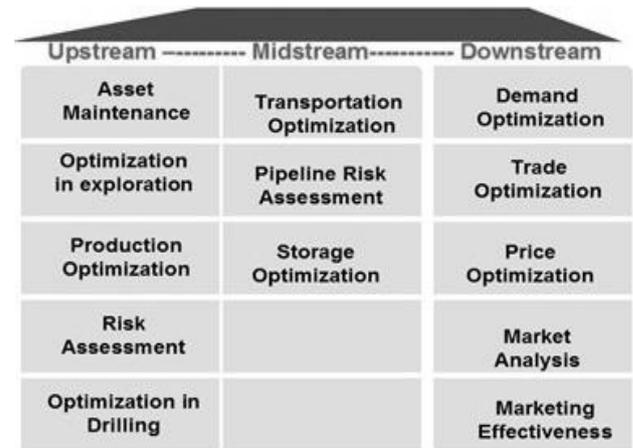


Fig. 3. Predictive analytics steps to be carried out in the pipeline system

3. Results and Discussion

The analysis of the ecological condition of the surface air layer of the Bohorodchany district was carried out based on the constructed maps of the distribution of concentrations of harmful substances, concentration coefficients, coefficients of ecological danger and the map of the total pollution indicator (Fig. 4).

Analyzing the state of atmospheric air in general, we can make the following conclusions:

- the percentage of oxygen in the air of main gas pipelines decreased, in some places to 20.175 %. This decrease is especially observed in the western part of the study area, where the network of gas pipelines is the densest. The highest oxygen content in the air is in the southwestern and northeastern parts because they are at some distance from the pipelines;
- the content of carbon monoxide is highest in places with the lowest concentration of oxygen and in the same areas a slightly higher content of carbon dioxide is found, and its highest concentration is in the west near the village of Mizhhiria;
- NO_x and SO_x have a mutually reinforcing effect;
- the most polluted air is found along the main gas pipelines, especially in the western part of the node where their network is the densest. The boundaries of

areas with anomalous values almost coincide, so the snow cover is most polluted in the following places: in the western part near the village of Lovagy, in the south – in the village. Starunia and its environs, in the east – in

the village of Lypivka. Particularly significant air pollution was found between the villages of Bohorodchany and Pkhovannia in the territory of the main gas pipelines management.

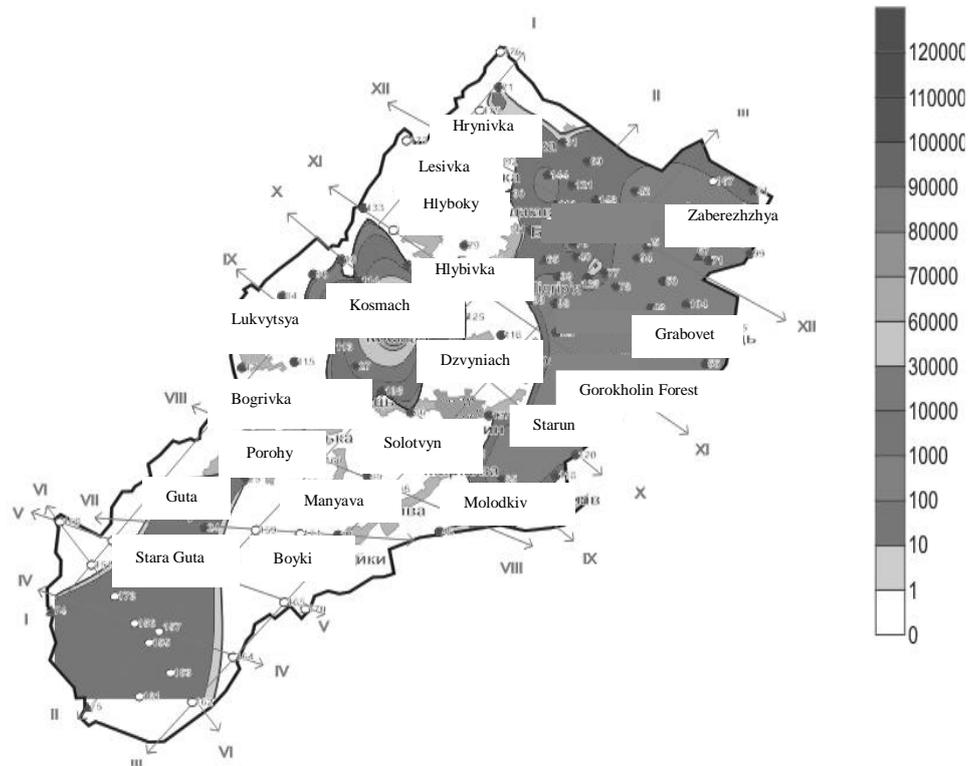


Fig. 4. Comprehensive map of the current ecological situation at the Bohorodchany node

In the snow cover, we found the distribution of such heavy metals as copper, zinc, lead. Areas with concentrations other than zero were found in rugged terrain in the west in the village of Lovagy. This also explains the pollution of heavy metals at this point – the result of cross-border transfers. In addition to heavy metals found in the snow cover, the distribution of other compounds was analyzed: carbon dioxide, carbon monoxide, oxides of nitrogen and sulfur, dust, gasoline, acetone and oxygen. The areas of distribution of these pollutants coincide with the wind rose for the study area. The main regularity of the research was also revealed - high concentrations of pollutants in areas with a dense network of roads, boiler houses and near natural gas transportation facilities.

Natural gas is known to have a negative effect on human life, as it has narcotic and toxic effects. Within the framework of the problem under consideration, the influence of the level of gas pollution due to the destruction of the main gas pipeline is of some interest. Calculations showed that the maximum amount of air pollution does not exceed 250–300 m. This distance can increase depending on the diameter of the pipeline and the direction of the gas jet flow during its depressurization.

In almost half of the cases, the gas ignites at the point of damage and the scale of air pollution decreases.

Therefore, pipeline transport negatively affects the environment of its laying. Therefore, the main task of environmental protection is to reduce the man-made impact during the construction and operation of gas pipelines, and, on the other hand, it is necessary to reduce the negative impact of natural factors on their safety and reliability. To solve this problem, we use the methods of environmental risk analysis (Mandryk et al., 2020; Yavorskyi et al., 2017).

The main factors of environmental risk of accidents on gas pipelines can be divided into two groups – man-made and natural. Man-made defects include pipes, installation errors, non-compliance with the profile and plan of the trench for laying the pipeline, various damages during earthworks, etc. To reduce such factors, it is necessary to strictly adhere to technological discipline and timely conduct control diagnostic measures. Natural factors include corrosion of various types and mechanical action of soils. The intensity of these processes is characterized by regional features of the territory. The most important of them are soil temperature

and humidity, which depend on the morphological characteristics of the terrain.

The linear part of gas pipelines is a potentially dangerous object and has a large energy potential that can adversely affect the environment. Therefore, it is important to solve the problem of zoning within the route and forecasting the parameters of dangerous areas for the population and territories (Mandryk et al., 2020). When choosing methods for assessing the risk of accidents on main gas pipelines, it is necessary to pay attention to cartographic and modelling methods. Simulation allows not only to quickly predict but also develop recommendations for reducing the risk and eliminating the consequences of emergencies (Yavorskyi et al., 2017).

Consider the method of calculating the detonation zone and the distance of the cloud of the explosive mixture during an accident on the main gas pipeline. It is necessary to take into account that accidents during depressurization of gas pipelines are accompanied by the following processes: gas leakage before shut-off valves, shut-off valves closing, gas leakage from the emergency section of the gas pipeline, which is cut off by valves. In the points of damage, the gas leaks under high pressure into the environment (Fig. 5).



Fig. 5. The place of liquidation of the accident of the main gas pipeline Dolyna-Bilche-Volytsia

Due to the depressurization of the gas pipeline, methane rises into the atmosphere, and other gases and their mixtures are deposited in the surface layer. Mixing with air gases, a cloud of the explosive mixture is formed. According to statistics, almost 80 % of accidents are accompanied by fires and explosions. Fire and explosion hazards occur when the concentration of methane in the air exceeds 5 % by volume. Explosive combustion during accidents on gas pipelines occurs in one of two modes – deflection or detonation. During

operational forecasting, it is assumed that the process develops in the detonation mode (Hoff, 1993).

The distance to which the cloud of explosive mixture extends in the wind direction is determined by the empirical formula [8]:

$$L = 25\sqrt{M/V} \quad (1)$$

where M is the mass of the second gas consumption, kg/s; 25 is the coefficient of proportionality; V is wind speed, m / s.

The boundary of the detonation zone with radius r_0 as a result of gas leakage in the case of depressurization of the pipeline is determined by the formula:

$$r_0 = 12,5\sqrt{M/V} \quad (2)$$

The mass second flow rate of gas M from the pipeline for the critical leakage regime, when its main parameters (flow rate and leakage rate) depend only on the parameters of the depressurized pipeline, is determined by the formula:

$$M = \psi \cdot F \cdot \mu \sqrt{P_r/V_r} \quad (3)$$

where ψ is the coefficient that takes into account the gas flow rate from the source (for the sound leakage rate $\psi = 0.7$); F is the area of the leakage hole, which is taken to be equal to the cross-sectional area of the pipeline, m^2 ; μ is gas consumption factor, which takes into account the shape of the hole (for calculations it is taken equal to 0.8); P_r is the gas pressure in the pipeline, PA; V_r is the specific volume of transported gas, which is determined from the equation:

$$V_r = R_0 \frac{T}{P_r} \quad (4)$$

where T is the temperature of the transported gas, K; R_0 is the specific gas constant, which is determined by the partial gas content q_k and molar masses of the components of the mixture from the ratio:

$$R_0 = 8314 \sum_{k=1}^n \frac{q_k}{m_k} \quad (5)$$

where 8314 is the universal gas constant, J/(kmol · K); m_k is the mass of components, kg / kmol; n is the number of components.

When forecasting the consequences of accidents on the gas pipeline, the wind direction in the detonation zone is taken into account, assuming that the boundary of the detonation zone extends from the pipeline in the wind direction to a distance of $2r_0$. In the case of early prediction, the detonation zone spreads in the form of bands along the pipeline with a width of $2r_0$ on each side. This is because the cloud of the explosive mixture can spread in any direction from the pipeline, depending on the direction of the wind.

For calculations, the temperature of the transporting gas is 40°C. The content of ordinary gas in the absence

of data can be taken in the ratio: methane – 90 %, ethane – 4 %, propane – 2 %, H-butane – 2 %, isopentane – 2 %.

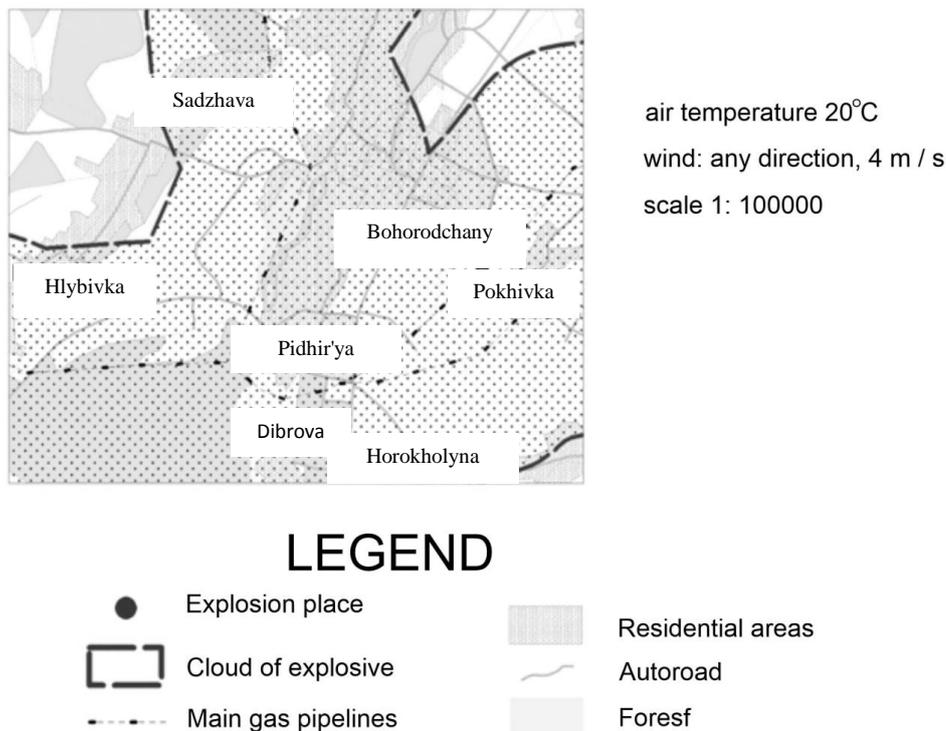


Fig. 6. Modelling of the detonation zone with possible depressurization of the pipeline

The area of possible spread of the explosive mixture on the topographic maps is indicated in the form of a circle, semicircle or sector. The center of the circle, semicircle or sector coincides with the place of depressurization of the pipeline (chosen arbitrarily):

1. At a predicted wind speed of 0.5 m/s, the detonation zone has the form of a circle with a radius of r_0 .

2. At the predicted wind speed of 0.6–1 m/s, the detonation zone has the form of a semicircle. The angle of the section is equal to 180°, the bisector of the angle coincides with the axis of distribution of the cloud and is oriented in the wind direction.

3. At the predicted wind speed of more than 1 m/s, the detonation zone has the form of a sector with a radius of $2r_0$. At a wind speed of 1.1–2 m/s, the angle of the sector is 90° and at a speed of more than 2 m/s, it is 45°.

According to the above method, calculations of the detonation zone and the range of the cloud of the explosive mixture at different wind speeds were performed.

The results obtained:

- at 0.4 m/s: $L = 4325$ m; $r_0 = 2162.5$ m;
- at 0.8 m/s: $L = 3075$ m; $r_0 = 1537.5$ m;
- at 3 m/s: $L = 1581$; $r_0 = 787.5$ m.

4. Conclusions

– The main cause of gas pipeline accident is depreciation and metal corrosion, which are caused by local climate conditions.

– Ecological damage is the main adverse effect of such accidents.

– The use of cartographic and modelling methods to assess the impact of the detonation zone and the range of the explosive mixture cloud during accidents on main gas pipelines allows forecasting and helps to develop recommendations for reducing the risk of dangerous situations. This, in turn, will reduce the negative impacts on the environment, infrastructure, as well as prevent human losses.

– To reproduce the detonation zone for the speed of 0.4 m/s, a circle of radius r_0 was drawn, for the speed of 3 m/s – a sector (angle 45°, radius $2 r_0$), for the speed of 0.8 m/s – a semicircle with a radius of average r_0 and $2 r_0$.

– After analyzing the results, we can conclude that at this direction of the wind during the accident on the pipeline, a large part of the village of Bogorodchany, with about 10 thousand inhabitants, as well as highways, get into the area of the spread of a cloud of explosive mixture.

References

- Cruz, A. M., & Krausmann, E. (2009). Hazardous-materials releases from offshore oil and gas facilities and emergency response following Hurricanes Katrina and Rita. *Journal of Loss Prevention in the Process Industries*, 22(1), 59-65.
- Grudz, V., Grudz, Y., Zapukhliak, V., Chudyk, I., Poberezhny, L., Slobodyan, N., & Bodnar, V. (2020). Optimal gas transport management taking into account reliability factor. *Management Systems in Production Engineering*, 28(3), 202–208. doi: <https://doi.org/10.2478/mspe-2020-0030>
- Hoff, A. M. (1993). An Experimental Study of the Ignition of Natural Gas in a Simulated Pipeline Rupture. *Combustion and Flame*, 49, 51–55.
- Jo, Y. D., & Ahn, B. J. (2002). Analysis of hazard areas associated with high-pressure natural-gas pipelines. *Journal of Loss Prevention in the Process industries*, 15(3), 179–188.
- Mandryk, O., Vytyaz, O., Poberezhny, L., & Mykhailiuk, Y. (2020). Increase of the technogenic and ecological safety of the natural gas transportation due to displacement of explosive mixtures with nitrogen. *Archives of Materials Science and Engineering*, 1(106), 17–27. doi: <https://doi.org/10.5604/01.3001.0014.5929>
- Maruschak, P., Bishchak, R., Prentkovskis, O., Poberezhnyi, L., Danyliuk, I., & Garbinčius, G. (2016). Peculiarities of the static and dynamic failure mechanism of long-term exploited gas pipeline steel. *Advances in Mechanical Engineering*, 8(4), 1687814016641565. doi: <https://doi.org/10.1177/1687814016641565>
- Peekema, R. M. (2013). Causes of natural gas pipeline explosive ruptures. *Journal of Pipeline Systems Engineering and Practice*, 4(1), 74–80.
- Yavorskyi, A. V., Karpash, M. O., Zhovtulia, L. Y., Poberezhny, L. Y., & Maruschak, P. O. (2017). Safe operation of engineering structures in the oil and gas industry. *Journal of Natural Gas Science and Engineering*, 46, 289–295.