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APPLICATION OF FORMALIZED MODELS OF EVENTS FOR EVALUATION OF DANGER AND ACCIDENT ASSESSMENT OF THE COMPRESSOR STATION OF THE MAIN PIPELINE

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Abstract. An effective approach to solving the problem of reducing man-made hazards is the use of specialized systems for forecasting and minimizing risks. The theoretical basis for hazard assessment is probabilistic safety analysis (IAB). The most common method of assessing the danger and accident is the development of formalized models of events is the use of logical-probabilistic models “failure tree” (FTA) and “event tree” (ETA). These methods are widely used in the world to analyze the risk of accidents at facilities with increased levels of danger. They are used both for the preliminary analysis of safety during the development of recommendations for reducing the level of risk and for investigating the causes of accidents at hazardous facilities. In Ukraine, such methods are used in the development of safety declarations for high-risk facilities. Considering a great number of hazards inherent in the operation of main pipelines, it is important to understand which of these risks are most critical. The specifics of their operation is directly related to the risk of cascading accidents. The purpose of the work is to establish criteria and assess the danger of accidents at the compressor station of the main gas pipeline.

Keywords: danger, risk, logical-probabilistic models, “failure tree”, “event tree”, main gas pipeline.

1. Introduction

The problem of prevention of man-made accidents is becoming more relevant every year because the number and severity of consequences of accidents have a general tendency to increase. Using foreign and domestic research and development, a generally accepted concept of their prevention, which is based on accident risk assessment and analysis, has been developed.

The greatest risk of accidents and dangers during operation of a pipeline transport, which significantly affects the state of the technogenic safety, is an excessive service life of the main equipment and an unsatisfactory condition of the pipelines themselves (Zhovtulya, 2015; EGIG; Savonin .et al., 2015). About 80 % of gas pumping units at compressor stations have been operated for more than 30 years and are obsolete both physically and morally (Vovk et al., 2017; Khrutba et al., 2017). Therefore, the study of the possibility of using formalized models of events to predict emergencies at main pipelines and compressor stations is relevant and timely.

The majority of main gas pipelines (MG) have an underground structural scheme of laying, which is affected by corrosive soils. Stress-corrosion cracking (SCC) of metal is currently one of the main and most common causes of failure of main pipelines. This type of damage includes longitudinal cracks that are formed on the outer surface of pipelines in areas with damages of the insulating coating under the action of corrosive environment and a stress-strain factor under cathodic polarization (Rybakov et al., 2014). Corrosion accounts

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for up to 25 % of all accident reports that kill people (EGIG; Savonin S. et al., 2015). In Ukraine, among the causes of accidents, there is a subjective factor associated with the negligent treatment of the pipeline or violations of the requirements for its operation.

Live corrosion cracking (CRC) of main gas pipelines is another major cause of their failure. As a rule, most accidents through the CRC route occur in the 20 km zone after the compressor station along the gas line. Besides contact with the soil electrolyte in areas of damage to the insulating coating, the metal of the pipe in this area is subject to additional exposure to elevated gas temperatures and high levels of vibration, which under certain conditions can cause stress corrosion cracks.

The authors (Makovei, 2010) note that most of the factors that caused accidents most often cannot be predicted when designing a pipeline. In particular, modern techniques allow us to take into account the corrosion factors that occur in the metal of pipes during their operation (so-called metal ageing), as well as, partially, the impact of soil landslides, while subjective factors are ignored during the design.

According to statistics, the degree of accidents at pipeline transport is as follows: in 90 % of cases, the content is released through a hole in the wall of the pipeline until the leakage is stopped and in 10 % of cases, there is a complete rupture of the pipeline (Citizen et al., 2002).

2. The experimental part

Probabilistic safety analysis (PSB) is the theoretical basis for hazard assessment. Among many problems that need to be addressed urgently, the protection of the population and territories from man-made emergencies is important. Risk assessment (probability) of accidents with the use of probabilistic structural and logical models involves possible deviations of the parameters (violation of the modes) of the process; the reasons for these deviations; mechanical failures and failures of equipment elements; failures of monitoring systems, alarm systems, automatic control systems and emergency protection systems; staff errors.

During the research of the reasons of deviations, failures of the equipment and fittings, breakdowns, and also the possible technological reasons caused by infringement of operating modes of functionally connected devices are considered.

The hazard analysis, using the failure tree, is oriented on potentially dangerous events. It implies identification of all the factors that may contribute to the accident. Based on the results of this analysis, an approximate graph – the tree – is build. Hazard analysis using a potential event tree explores a group of events that lead to accidents (Henley, Kumamoto, 1984).

Probabilistic models of the danger assessment. Fault Tree Analysis (FTA) is a method of deductive thinking where the logical connection between potential accidents and the corresponding causes can be represented by tree diagrams. The fault tree is a directed logical tree that describes the occurrence of accidents from result to reason (Wang, 2018). The FTA methodology is currently widely used in system safety and reliability engineering, and in all major fields of engineering.

Event Tree Analysis (ETA) uses the same logical and mathematical methods as failure tree analysis. Event trees use an inductive approach, while failure trees use a deductive one.

An Event Tree Analysis (ETA) is an inductive procedure that shows all possible outcomes resulting from an accidental (initiating) event, taking into account whether installed safety barriers are functioning or not, and additional events and factors. By studying all relevant accidental events (that have been identified by a preliminary hazard analysis), the ETA can be used to identify all potential accident scenarios and sequences in a complex system. Design and procedural weaknesses can be identified, and probabilities of the various outcomes from an accidental event can be determined (Rausand, 2004).

Event trees are used to identify the consequences of emergencies that develop within the technological process. Building an event tree is more difficult than a failure tree, but it allows analysis of the effectiveness and reliability of protection and provides an estimate of the scale of the consequences of accidents

For each accidental event, one should identify:

- The potential accident progression;
- System dependencies;
- Conditional system responses.

In practical applications, there are discussions about what should be considered as an accidental event (e.g., should one start with a gas leakage, the resulting fire or an explosion). Whenever feasible, we should always start with the first significant deviation that may lead to unwanted consequences. Additional events and/or factors should be listed together with barriers, as far as possible in the sequence, in which they may take place.

Development of formalized models of events. Major accidents are usually characterized by a combination of random events that occur with different frequencies at different stages of occurrence and development of the accident. Logical and graphical methods of analysis of the failure tree and the event tree are used to identify causal relationships between these events. The analysis of the failure tree reveals a combination of failures (damage) of equipment, incidents, personnel errors, and external influences that lead to the main event (emergency).

The event tree method is used to analyze potential causes of an emergency and calculate its frequency (based on knowledge of the frequencies of the initial events). The frequency of each emergency scenario is calculated by multiplying the frequency of the main event by the conditional probability of the final event.

3. Results and Discussion

The hazard assessment using event models was carried out on the example of the operation of the gas system of the Krasyliv compressor station of the Dashava-Kyiv main gas pipeline.

The main scenarios of probable accidents on gas pipelines are related to rupture of pipes at the full cross-section and gas leakage into the atmosphere in the critical mode (at the speed of sound) from both ends of the gas pipeline (upstream and downstream). The length of the gap and the probability of gas ignition have some connection with the technological parameters of the pipeline (pressure, diameter) and with the characteristics of the soil (density, rocky inclusions).

Large diameter pipelines (1000–1400 mm) are characterized by long ruptures (50–70 m or more) and a high probability of gas ignition (0.6–0.7).

Gas combustion can occur in two main regimes. The first one commonly occurs in the form of two independent (weakly interacting) flat jets of a flame with an orientation close to the axis of the gas pipeline. This is typical of mainly large diameter pipelines (“jet” flame regime). The second one should include the resulting (by gas consumption) column of fire with an orientation close to vertical (combustion “in the pit”). This regime of gas combustion is more typical of pipelines of a relatively small diameter.

The amount of natural gas capable of participating in the accident depends on the diameter of the pipeline, the operating pressure, the place of rupture, the time of identification of the rupture, the location and reliability of the linear valve.

The most dangerous areas of emergency depressurization of gas pipelines are:

– sections of gas pipelines after compressor stations (up to 5 km) – non-stationary dynamic loads;

– sections of gas pipelines at connection nodes;

– areas of underwater crossings;

– areas passing near settlements and areas with a high level of anthropogenic activity (areas of construction, intersection with roads and railways).

The process of gas hazard identification at the object under investigation was performed using the failure tree analysis (FTA) and the event tree analysis (ETA). These methods can include simultaneous failures of technical components and failures due to human error (human factor). This allows a broader analysis of the causal factors that lead to the final event such as an accident or technical failure.

The graphical form of the failure tree, which is used to analyze the causes of depressurization of the main gas pipeline, is presented in Fig. 1. The top of this tree is an undesirable event which is the release of gas due to depressurization or destruction of the pipeline.

The sequence of events that leads to an undesirable event at the top, form the branches of the tree that are represented by pipeline defects, personnel errors, corrosion, various loads, etc.

Intermediate events are indicated by rectangles; the initial prerequisite events are shown by circles with numbers. Logical signs “AND” and “OR” are used for communication between events in “nodes” of a tree.

 “AND” means that an output event occurs if all input events occur simultaneously

 “OR” means that an output event occurs if any of the input events occurs.

The failure tree gives a clear idea of relationships within the system and how and for what reasons various adverse events which may affect the loss of tightness of the main gas pipeline occur.

In the ETA event tree method, the analysis begins with finding the causes (threatening factors) that lead to emerging threats. In the event tree scheme, the areas of the main event (initiating event) and event trees (sequence of probable events) are distinguished. In this case, the method allows the analysis of complex security systems and emergencies. The probability of emergencies using the event tree method is shown in Fig. 2.

For the connection node to the MG, gas piping and gas equipment of the CS, accident scenarios can be described in generalized form as follows: depressurization of the pipeline or unit with the release (leakage) of natural gas into the environment → interaction of a gas flow with environmental components → ignition initiators → influence of accident factors on recipients → injuries or casualties among recipients.

Consider the sequence of the accident on the underground pipelines-branches to the CS. Due to a number of reasons indicated in the failure tree, there is a rupture of the underground technological gas pipeline → formation of a pit in the ground → formation of a primary air compression wave due to expansion of compressed gas into the atmosphere → scattering of pipe fragments and soil fragments → gas leakage→

ignition of the flowing gas with the formation of a "pillar" of flame → formation of the secondary air compression wave during ignition of the gas → getting people, buildings and equipment into the area of thermal impact from the fire → death or burns of varying severity and injuries caused by air compression waves and fragments; and destruction or damage to the equipment of the CS.

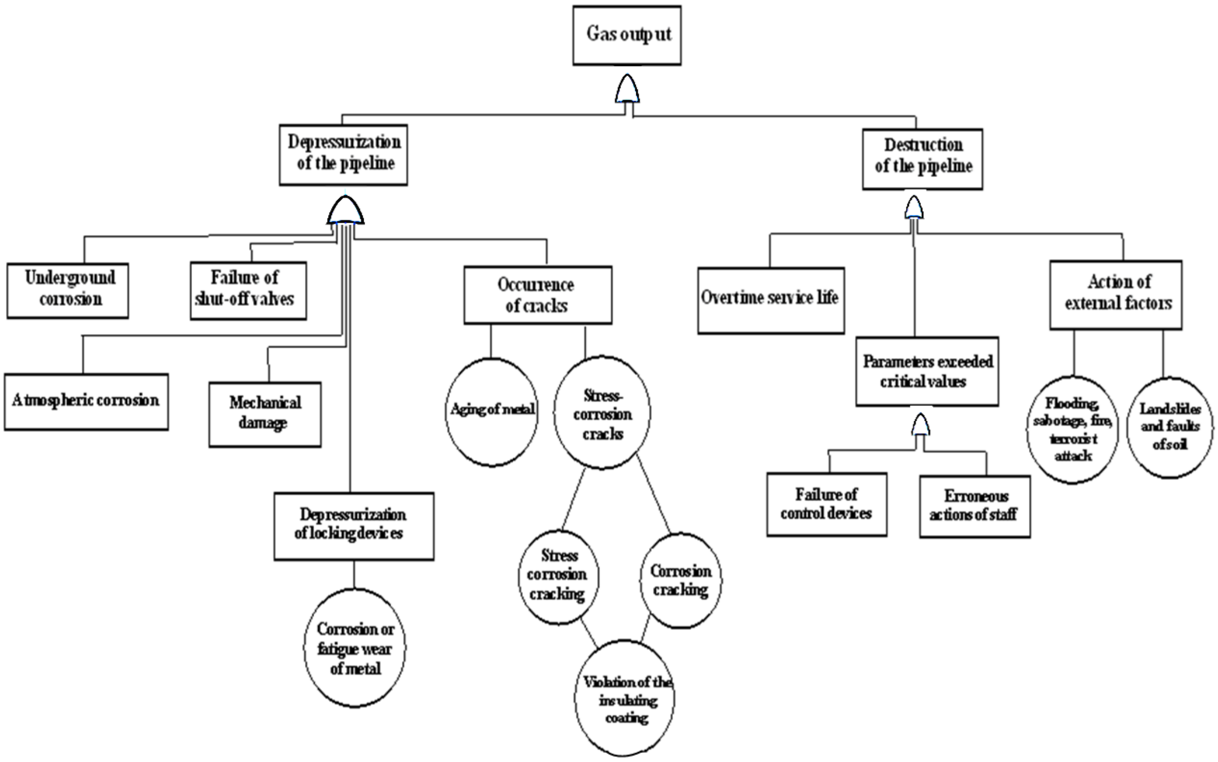

Fig. 1. Failure tree of accidents at the MG compressor station

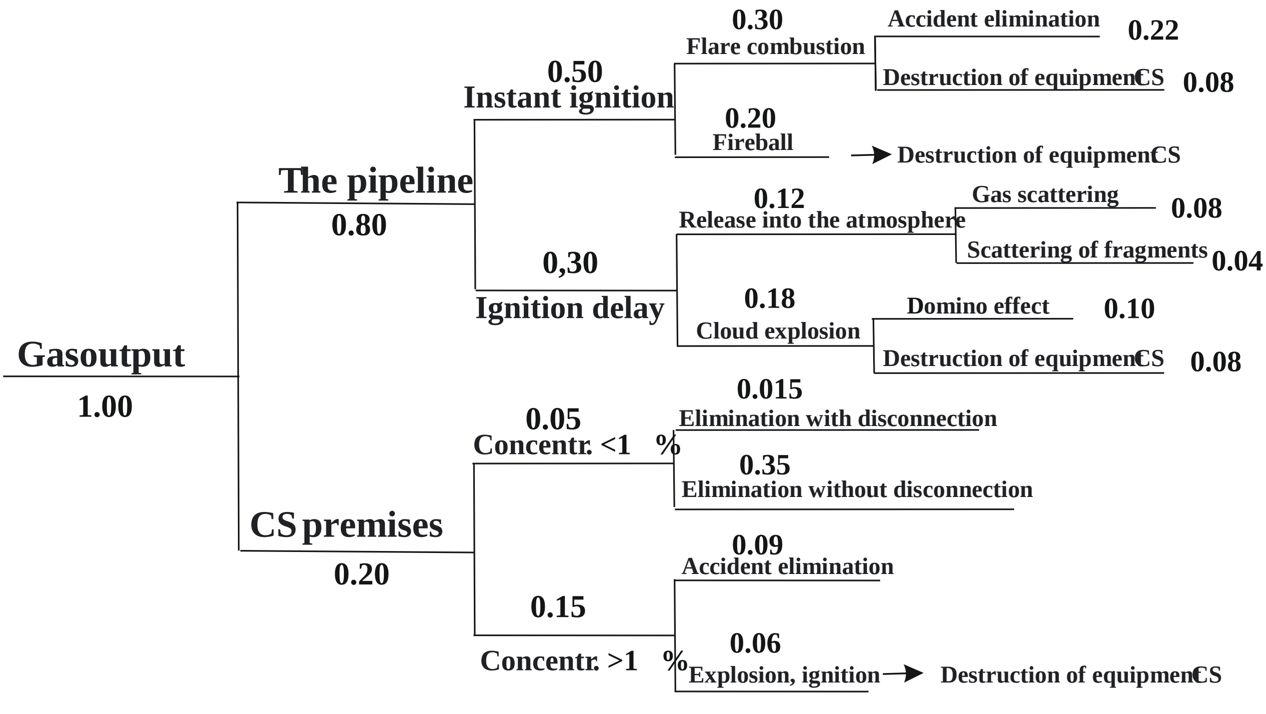

Fig. 2. Event tree in case of accidents at the MG compressor station

According to another scenario, events may develop as follows: rupture of the underground technological gas pipeline → formation of a pit in the ground → formation of an air compression wave → scattering of pipe fragments and soil fragments → gas leakage from the pipeline in the form of a column loop → scattering of leakage gas without ignition → getting people, buildings and equipment in the area of pressure or gas clouds → human injuries and damage to equipment as a result of exposure to air compression wave and fragments; and asphyxia of people when exposed to a gas cloud → atmospheric pollution by natural gas.

For above-ground external gas pipelines, the emergency can develop as follows: rupture of the above-ground external gas pipeline → formation of an air compression wave at the time of rupture → scattering of pipe fragments → leakage of gas jets from the ends of the broken gas pipeline → failure of fire extinguishing systems → thermal impact of the fire on technological equipment, buildings and personnel who were outside the premises → destruction or damage to equipment, buildings; death or human burns of varying severity, as well as injuries from the compression airwave or fragments.

An even more dangerous situation can arise in the event of a fire initiator during an emergency depressurization of the pipeline with the following consequences: rupture of the overhead external gas pipeline → formation of an air compression wave at the time of rupture → scattering of pipe fragments → gas leakage from the ends of the broken pipeline → high-speed jets →ignition of the flowing gas with the formation of flare combustion → failure of fire extinguishing systems → thermal impact of the fire on process equipment and on people who were outside the premises → destruction or damage to equipment and structures at the site; death or human burns, injuries from the compression airwave or fragments.

Calculation of factors causing damage. The values of the indicators of the factors of damage in case of accidents on the pipeline branches of the MG and gas pipelines of the CS were estimated in this work. The calculation of the pressure wave parameters during gas combustion in the open space was performed for different distances. The main component of fuel gas is methane. Gas mass m_g = 2232 kg and m_g = 127 kg.

The air compression wave occurs during the rupture of the main gas pipeline as a result of the expansion of natural gas transported under high pressure. The excess pressure ΔP, which develops during the combustion of gas in the open space was calculated by the formula:

$$\Delta P = P_0\left(\frac{0{,}8\times m_r^{\ 0{,}33}}{r}+\frac{3\times m_r^{\ 0{,}66}}{r^2}+\frac{5\times m_r}{r^3}\right), kPa$$

where P_0 is the atmospheric pressure (101 kPa); r is the distance from the geometric center of the gas cloud, m; m_r – reduced gas mass, kg.

$$m_r = \left(\frac{Q_c}{Q_0}\right)\times m_g \times Z, kg$$

where Q_c is the specific heat of combustion of methane, J / kg; Q_0 is a constant equal to 4.52x106J / kg; Z – participation coefficient, it is allowed to take Z = 0,1; m_g – mass of gas released into the environment as a result of the accident, kg

The pulse of the pressure wave is determined by the formula:

$$i = \frac{123\times m_r^{\ 0{,}66}}{r}, Pa\cdot s$$

The results of the calculations are shown in Fig. 3 and 4.

During the combustion of the gas-air mixture in the open space in the event of damage to the gas pipeline of the connection node, destruction of the compressor station building is possible with damage to the equipment and chain development of the accident. Due to the action of excessive wave pressure on other buildings, moderate damage is possible (damage to frames, doors, glazing). Combustion of the gas-air mixture in the open space in case of destruction of the gas pipeline will cause much less damage to the equipment of the CS.

The calculation of the zones of the impact factors of the explosions using the TNT equivalents of the explosion in the gaseous medium was performed according to (NAOP).

The size of a torch in the case of a jet leakage of the compressed gas from the damaged pipelines that increases the danger of thermal effect was also estimated (Ponomarev et al., 1997). The torch length $L_F = K\cdot G^{0,4}$ and the torch width $D_F = 0{,}15\cdot L_F$ was determined, where G is the gas flow rate, kg/s; K is the empirical coefficient, which is assumed to be 12.5.

It is established that the area of the most dangerous thermal influence of flare combustion determined by the size of the torch is 233 m. The results of the calculations are shown in Table 1.

The specific features of the compressor station are:

– high productivity and a permanent technological connection of the objects with the supply gas pipelines objectively cause the release of large volumes of natural gas into the environment in case of an accident;

– high density of the installation of technological equipment;

– densely equipped sites with electrical equipment and power supply lines that cause an increased probability of gas ignition in case of an accident;

– the significant cost of the installed equipment.

Thus, the studied risk factors for accidents at the compressor station of the main gas pipeline suggest that a close location of supply pipelines objectively causes the release of large amounts of natural gas in the event of an accident, significantly increasing the risk of a combination of danger factors of the accidents and can provoke the development of chain accidents.

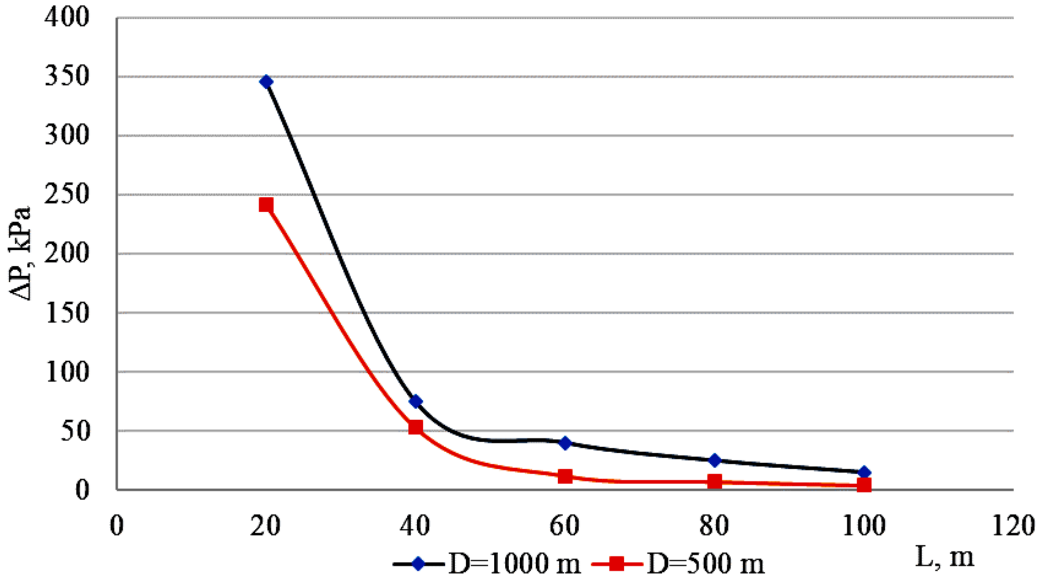

Fig. 3. Excess pressure of the explosion
at a distance from the geometric center of the cloud

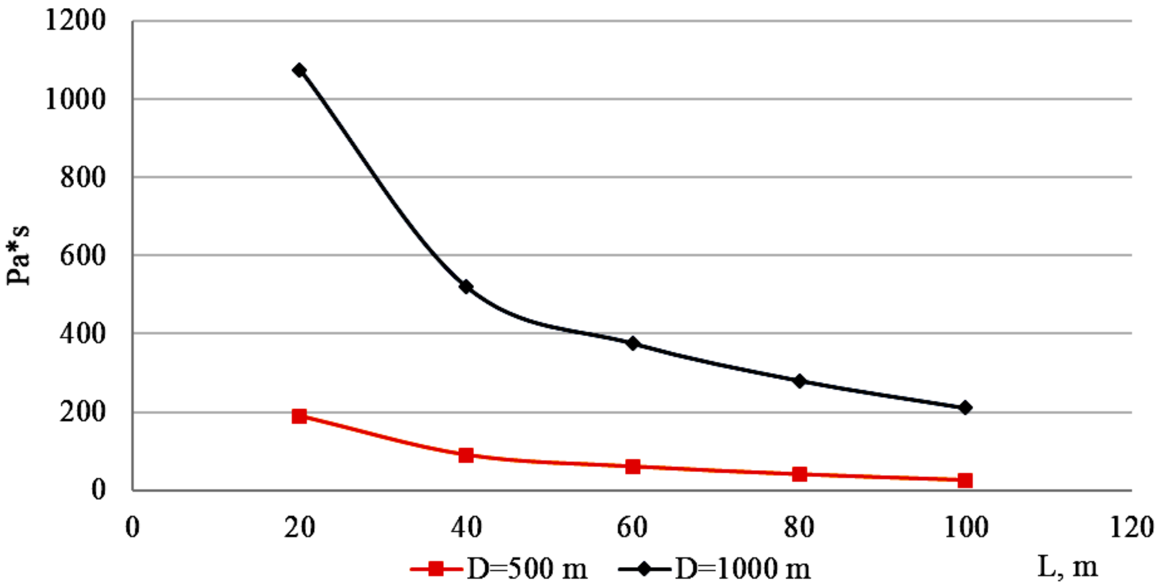

Fig. 4. The pulse of the shock wave
at a distance from the geometric center of the cloud

Table 1

Indicators of damage factors in the event of an accident on gas pipeline strapping and MG connection nodes to the CS

The name of the parameter		Pipeline from MG	Strapping line
Conditional diameter, mm		1 000	500
Working pressure, MPa		5.5	5.5
Danger category		I	III
The radius of the LCLF zone, m		127.8	47.78
Height of the LCLF zone, m		255.6	95.56
Length of pipeline rupture, m		70	16
Mass of gas at explosion, kg		2 232	127
TNT equivalent, kg		1213	69
Radius of the zone of destruction at the pressure drop of the shock wave (kPa), m	100.0	31	4
	70.0	46	7
	28.0	79	11
	14.0	231	32
	5.0	463	64
Mass gas leakage rate, kg / s		1 504	374
Torch length, m		233	134
Torch diameter, m		35	20

4. Conclusions

The factors that affect the integrity of gas pipelines have been established and used for the development of a failure tree. The failure tree provides a clear explanation for the reasons and mechanisms of various adverse events that may affect the leakage of the main gas pipeline. The developed event tree graphically demonstrates the nature of the development of probable accidents and their causal relationships. This basic concept is used for risk assessment.

Potential scenarios of occurrence and development of accidents are shown on the logical trees consecutive events from the initial event to the final one.

The estimated radii of the zones of damage caused by an explosion due to emergency depressurization of the gas pipelines of the CS and the MG-CS connection node demonstrate that in the case of depressurization of one of them, the buildings and equipment fall into zones of different destruction levels and contribute to the increase of the accident scale by the effect of “dominoes”.

In addition, in the event of an accident on the gas pipeline of the connection node, the compressor station building is included in the destruction zone. Under adverse conditions of the accident, its equipment will be damaged.

The use of formalized models of events (FTA and ETA) allowed to identify the factors of emergency and sequence of the accident development events and to assess the risks for the compressor station of the main gas pipeline.

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