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Original article

Development of an Approach to Assess the Consequences of Fuel-Air Mixtures Explosions Taking into Account the Development Features

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Abstract
Introduction. In the study of the problem of the impact of negative factors from explosions at gas stations on people and the infrastructure of settlements, a probabilistic approach is often used. The limitation of this approach is that when it is implemented, the concept of clutter of the surrounding space does not reflect the relationship between the area occupied by buildings and the total area affected by the shock wave. Therefore, this article is devoted to the development and justification of an approach to assessing the consequences of explosions of fuel-air mixtures (FA), taking into account the peculiarities of the development of settlements. The work objective is to develop an approach for assessing the consequences of explosions of fuel-air mixtures, taking into account the development features. The solution to this problem will facilitate decision-making for the development of effective protective measures for surrounding objects.
Materials and Methods. The authors have conducted an analytical review of the research results in the field of study and the existing approaches to assessing the consequences of explosions at filling stations (FS) and gas stations (GS), based on the specific conditions of their location on the territory of settlements.
Results. An approach has been developed to assess the consequences of explosions of fuel-air mixtures, taking into account the development features. The main causes, types of accidents with an explosion at a gas station and the scale of their consequences have been identified. Along with the theoretical justification of the issue under consideration, the authors provide a detailed description of the applied research methodology, as well as the characteristics of the objects of research, taking into account their location. When calculating the consequences of explosions of fuel-air mixtures, it was proposed for the first time to use a development density factor equal to the ratio of the area of the existing facilities to the total area of the territory affected by the shock wave. This approach justifies the need to apply additional protective measures in the areas where gas stations are located. The methods of analysis used are described in detail with justification of the reliability of the measurement results.
Discussion and Conclusion. The application of the approach proposed in the article for calculating the consequences of an explosion of fuel-air mixtures, taking into account the development density, makes it possible to control the location and the level of risk from possible explosions at gas stations in a real situation. The proposed approach for calculating the consequences allows you to quickly assess possible risks in real time and plan specific measures to minimize them in accordance with the existing situation in the area of the gas station.

Keywords: filling (gas) station, risk assessment, methodology, deflagration, explosion, calculations, experiment, development.

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Научная статья

Разработка подхода для оценки последствий взрывов топливно-воздушных смесей с учетом особенностей застройки

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Аннотация

Введение. При исследовании проблемы воздействия на людей и инфраструктуру населенных пунктов негативных факторов, возникающих при взрывах на заправочных станциях, зачастую применяется вероятностный подход. Ограничение данного подхода состоит в том, что при его реализации понятие загроможденности окружающего пространства не отражает соотношения между площадью застройки и общей площадью, подверженной воздействию ударной волны. Поэтому данная статья посвящена вопросам разработки и обоснования подхода к оценке последствий взрывов топливно-воздушных смесей (ТВС) с учётом особенностей застройки населённых пунктов. Целью работы явилась разработка подхода для оценки последствий взрывов топливно-воздушных смесей с учетом особенностей застройки. Решение данной проблемы будет способствовать принятию решений для разработки эффективных защитных мероприятий для окружающих объектов.

Материалы и методы. Авторами проведён аналитический обзор результатов исследований в изучаемой области и существующих подходов к оценке последствий взрывов на автомобильных заправочных станциях (АЗС), газозаправочных станциях (АГЗС), исходя из конкретных условий их расположения на территории населённых пунктов.

Результаты исследования. Разработан подход для оценки последствий взрывов топливно-воздушных смесей с учетом особенностей застройки. Выявлены основные причины, виды аварий со взрывом на АЗС и масштабы их последствий. Наряду с теоретическим обоснованием рассматриваемого вопроса, авторами приведено подробное описание применённой методики исследования, а также характеристика объектов исследования с учётом их месторасположения. При расчете последствий взрывов топливно-воздушных смесей впервые предложено использовать коэффициент плотности застройки, равный отношению площади существующих объектов к общей площади территории, подверженной воздействию ударной волны. Данный подход обосновывает необходимость применения дополнительных защитных мероприятий в районах расположения заправочных станций. Подробно описаны использованные методы анализа с обоснованием достоверности результатов измерений.

Обсуждение и заключения. Применение предлагаемого в статье подхода для расчета последствий взрыва топливно-воздушных смесей с учетом величины плотности застройки даёт возможность контролировать расположение и уровень риска от возможных взрывов на заправочных станциях в условиях реальной обстановки. Предлагаемый подход к расчету последствий позволяет оперативно в реальном масштабе времени и в соответствии с существующей обстановкой в районе расположения АЗС оценивать возможные риски и планировать конкретные мероприятия по их минимизации.

Ключевые слова: автозаправочная (автогазозаправочная) станция, оценка риска, методика, дефлаграция, взрыв, вычисления, эксперимент, застройка.

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Introduction. Accidental explosions often occur at automobile gas stations located in the immediate vicinity of places where a large number of people stay. The assessment of the consequences of such explosions is relevant and extremely important. The severity of negative impacts depends primarily on the presence and quality of obstacles to the propagation of the shock wave. Subsequent assessments are necessary to carry out corrective measures aimed at reducing the impact of negative explosion factors. These include the installation of any mechanical obstacles — protective barriers, trees, shrubs, etc. The effectiveness of protective measures in quantitative terms should be sufficient to reduce the risks to the minimum permissible values. At the same time, the assessment of hazards should have a visual representation.

In practice, it is not uncommon for regulated and unregulated pedestrian crossings, various buildings or public transport stops to be located near gas stations, including multi-fuel ones. At the same time, there are often no elementary obstacles from explosive objects on the way to them that contribute to reducing the explosive load.

The danger of severe consequences in case of accidents at gas stations is confirmed by Russian and international statistics. In particular, during the period from 2005 to 2016, 2–3 fires with victims occur annually at gas stations in our country, in which 4 people are injured or killed [1]. Similar cases occur in other countries, for example, [2] describes 50 typical cases of accidents at gas stations in China over the past 20 years.

The leading approach to the study of the problem of the impact of negative factors of explosions at gas stations on people and the infrastructure of settlements is the use of well-known techniques [3] implemented in various software packages. For example, the module "Fuel-air mixtures explosions. Calculations of the affected areas during fuel-air mixtures explosions"[1] allows us to comprehensively consider all the above mentioned parameters. For practical and research purposes, the methodology makes it possible to control the entered parameters, calculation logic, and assessment of the magnitude of the consequences in case of changes in local building conditions.

To analyze hazards, the researchers use methods of analyzing modes and consequences of failures. The type and cause of equipment failure of the most frequent accidents is an explosion caused by static electricity. In this regard, effective measures are usually proposed to eliminate accidents and mitigate the consequences. The research results are aimed at ensuring the possibility of risks reduction of operating gas stations.

Scientific sources devoted to the analysis of accidents with the explosion of liquefied petroleum gases indicate that their consequences often lead to significant material losses and human casualties. Hazard analysis for deflagration and detonation mode is usually performed by the analytical method described in detail in above methodology [3]. However, more complex numerical calculation methods are also used [4]. For example, with the software[2] help, the explosion scenarios are considered in conditions of complex area development in a three-dimensional representation, including in the case of an explosion inside a building. To analyze the deflagration hazard of fuel-air mixtures, the explosion pressure and flame propagation features of a pre-mixed mixture of liquefied petroleum gases (LPG) with air can be

[1] *Modul' «Vzryv TVS». Raschety zon porazheniya pri vzryvakh*. URL: https://toxi.ru/produkty/programmnyi-kompleks-toxirisk-5/moduli-toxirisk-5/modul-vzryv-tvs-raschety-zon-porazheniia-pri-vzryvah-tvs (accessed 22.12. 2022). (In Russ.).
[2] *BREEZE ExDAM. Modeling Software for EHS Professionals*. Trinity Consultants. URL: https://www.trinityconsultants.com/software/explosion/exdam (accessed 15.09.2022).

studied numerically. For example, in a closed pipeline at elevated initial pressures and temperatures. The results of such studies allow us to identify the greatest influence on the parameters of the explosion, for example, the initial pressure. Due to the general observed trend, there is an approach to predicting accidents and their consequences using the concept of risk. Features of the risk of LPG deflagration in difficult work situations, explosion risk assessment of related procedures and devices for the development of scientific and effective explosion protection measures are considered in work of Chinese researchers [5].

Safety and risk assessments studies are increasingly being used to manage hazardous materials management activities. The resulting models in risk analysis studies can be used, for example, for land use planning or for calculating the consequences of emergencies of already existing facilities. Some works present models for calculating the consequences of fires, explosions and toxic gas emissions for people, buildings and structures. The source of such models, as a rule, is a handbook on the calculation of consequences developed for the Ministry of Housing and Environment of the Netherlands, which provides a significant number of models [6]. In foreign literature, one can find sources that reveal the basic concepts in terms of the acoustic effects of the explosion and their physical characteristics [7].

Filling stations, their multi-fuel variants, single gas filling stations are quite complex socio-technical systems with dynamic relationships between various risk factors. Currently, the causal analysis of accidents related to the explosion of fuel-air mixtures is mainly focused on the study of aspects of human fault and equipment malfunction. In [8], 28 risk factors for gas explosions were identified. Nine of them, such as a flash, an electric spark and a local accumulation of gas, are the direct causes of gas explosion. 17 factors are related to operating actions, malfunction of ventilation systems and errors in safety management. They are indirect. The probability of gas explosion increases with an increase in the number of risk factors. The risks associated with the imperfection of state policy and legislative acts are among those that are poorly subject to management. It has been established that, compared with subjective risk factors, objective factors have a higher probability of causing a gas explosion due to associated risks.

There are a number of studies devoted to the comparative explosion consequences assessment based on different approaches. For example, in [9], simplified empirical models were used to assess explosion consequences. Nevertheless, in most cases, a methodology adopted by the international community and based on probabilistic models is used to assess the degree of vulnerability of people. The calculation results using different approaches have some differences, but all reproduce the real damage and predict the explosion consequences with sufficient accuracy.

Among Russian scientists, work is also underway to systematize the results of research on the damaging effects of air shock waves during gas-air mixtures explosions. Thus, in [10], various empirical dependences of the main parameters of the air shock wave on the distance were obtained on the basis of the universal method of energy similarity. A method has been developed for calculating the power of the damaging effect for a person who is in shelters of various degrees of protection.

The simplest example of noise impact assessment during explosions of fuel-air mixtures is presented in source [11]. According to the information presented in this paper, it is possible to determine the distance from the epicenter of the explosion, at which the sound pressure level is 140 dB, which is a critical value for a human auditory analyzer.

This article is aimed at developing an approach to identify the calculated values of the probability of occurrence of an event — the impact of a shock load on a person and environmental objects due to a possible explosion of the fuel-air environment, taking into account the development features on the ground, which are determined by a specially introduced formula. Such a calculation is carried out in a single computational paradigm with the possibility to set initial parameters and visually present the results to the user.

The analysis of the previously described research materials allowed us to establish that the nature and dynamics of the behavior and consequences of emergency situations at stand-alone gas stations directly depend on the characteristics of the surrounding area. The disadvantage of the analyzed methods is the absence of a factor in the calculations that takes into account the development features of the area. The objects that need to be considered may include public transport stops, residential buildings, regulated pedestrian crossings and other gas stations. They are characterized by a close location to places of one-time congestion and even mass stay of people with a population of 50 and more people.

The authors have also analyzed another type of materials — regulatory legal acts of the Russian Federation and came to the conclusion that at present there is some legal uncertainty in the application of a number of concepts used in justifying approaches to the placement and design of gas stations on the territory of settlements. In particular, the concept of "a place of mass stay of people", introduced by the law "On Countering Terrorism"[3], means the simultaneous presence of 50 or more people in a certain place. By the Decree of the Government of the Russian Federation[4] these places were ranked in three categories: with a population of up to 200 people — the third category, up to 1000 people — the second one and more than 1000 people — the first category. An object with a mass stay of people is a building or structure (except residential buildings) in which 50 or more people can be at the same time[5]. That is, in order to justify the risk of placing a potentially hazardous object or a place with a mass stay of people, it is necessary to consider only objects with a population of 50 or more people. It is quite difficult to imagine a stop with simultaneous presence of more than 50 people with the current saturation of cities with public transport. Current documents regulating the placement of gas stations, NPB-111-98* and SP 156.13130.2014[6,7] establish specific standards for the remoteness of gas stations from certain objects, buildings and structures, public roads, etc. However, instead of the concept of "public transport stop", as a rule, the wording "place of mass stay of people" is used. Since human life is the highest value and an absolute priority in justifying any approaches, it seems advisable to reduce the threshold for the number of places (objects) of mass stay of people or introduce the concept of "a place of gathering of people" with the establishment of a number of 20 or more people. Then public transport stops, regulated and unregulated crossings, etc. will fall under this definition.

Thus, the conclusion is that the use of the established approaches to assessing the consequences of possible explosions at gas stations can lead to a revision of the standards for their location within the boundaries of settlements, the degree of their emergency protection and the protection of objects located in the zone of possible impact of negative explosion factors.

Materials and Methods. To achieve the goal set in the work we use analytical modeling of the consequences of explosions of fuel-air mixtures with building density assessment on the territory of a hazardous object. This approach makes it possible to clarify the characteristics of the type of surrounding space, expressing it not only with a qualitative, but also with a quantitative measure and substantiate the need and priority of carrying out protective measures to reduce possible risks and damage.

[3] *O protivodeistvii terrorizmu*. Federal law of 06.03.2006 No. 35-FZ. State Duma. URL: http://www.consultant.ru/document/cons_doc_LAW_58840/ (In Russ.).

[4] *Ob utverzhdenii trebovanii k antiterroristicheskoi zashchishchennosti mest massovogo prebyvaniya lyudei i ob"ektov (territorii), podlezhashchikh obyazatel'noi okhrane voiskami natsional'noi gvardii Rossiiskoi Federatsii, i form pasportov bezopasnosti takikh mest i ob"ektov (territorii).* Decree of the Government of the Russian Federation No. 272 of 25.03.2015 (ed. 29.07.2020). Government of the Russian Federation. Electronic fund of legal and regulatory documents. URL: https://docs.cntd.ru/document/420264843?section=text (In Russ.).

[5] *Ob utverzhdenii Pravil protivopozharnogo rezhima Rossiiskoi Federatsii (s izmeneniyami i dopolneniyami).* Decree of the Government of the Russian Federation No. 1479. Government of the Russian Federation. Electronic fund of legal and regulatory documents. URL: https://docs.cntd.ru/document/565837297?section=text (In Russ.).

[6] *SP 156.13130.2014 Car refueling stations. Fire safety requirements*. Approved and put into effect by Order of the Ministry of Emergency Situations of Russia No. 221 of May 05, 2014. URL: https://docs.cntd.ru/document/1200110842 (accessed 15.12.2022). (In Russ.).

[7] *Normy pozharnoi bezopasnosti. Avtozapravochnye stantsii. Trebovaniya pozharnoi bezopasnosti. NPB 111-98**. Date of introduction 01.05.1998. Put into effect by Order of the GU GPS of the Ministry of Internal Affairs of Russia No. 25 of 23.03.1998. (In Russ.).

The methods of basic calculations are based on the use of the provisions of methodology [8], which allows determining the consequences of detonation or deflagration combustion of fuel-air mixtures containing propane, methane or gasoline. Additionally, area or length measuring instruments in 2GIS and similar programs were used. This made it possible to perform online measurements of areas or lengths on the displayed terrain.

As calculated parameters, the parameters laid down in manual [3] were evaluated, taking into account the provisions of [6]: significant or complete structural damage to buildings, the probability of eardrum rupture, survival as a result of pressure wave or lung damage. Due to the availability of mathematical logic of calculations, it is possible to implement an assessment of consequences as a result of the action of fragments as secondary factors of damage.

In total, the terrain features near seventeen gas stations located on the territory of Izhevsk, where such fuels as propane, methane or gasoline are used, were analyzed. Characteristic objects of key interest are presented in Table 1. For obvious reasons, these objects are depersonalized.

Table 1

Characteristics of the studied objects

No.	Fuel type	Features of the location, including the proximity of similar objects	Possibility of gathering of people
1.	Propane	In the line of sight there is a gas station at a distance of 95 m, next to which there is a bus stop	No
2.	Methane	Bus stop at a distance of 60 m	Yes
3.	Propane	High-rise building (5 or more floors) at a distance of 25 m	No, but the effect of secondary explosion factors — glass fragments is possible.
4.	Gasoline	In the line of sight there is a transport stop, as well as a 5-storey residential building	Yes

Results. Before performing the calculations, two tasks were set that were necessary to verify the reliability of the calculations:

– assessment of the correctness of the calculations of probabilities of the estimated parameters based on the probability function;

– assessment of the correctness of measuring areas and lengths in relation to objects on the ground.

Verification of the correctness and completeness of the solution to the first problem was performed on the conditions of solving the problem given in example No. 1 of methodology [3]. The solution to the second problem was confirmed in an experiment using a measuring "ruler" on the website of the public cadastral map of the Udmurt Republic[8]. The use of characteristic measurement points in the measurement experiment on the cadastral map showed the results of measurements along the length. Hence, the conclusion was made about the reliability of the measurement and the area on the ground. Figure 1 provides an explanation of the principle of performance of measurements. (obtained by the authors using a public cadastral map https://egrp365.org/map/?id=g2ApXz), Figure 2 provides a visual representation of the calculation result.

[8] *Public cadastral map of the Udmurt Republic EGRP 365*. Checking real estate. URL: https://egrp365.org/ (accessed 23.10.22). (In Russ.).

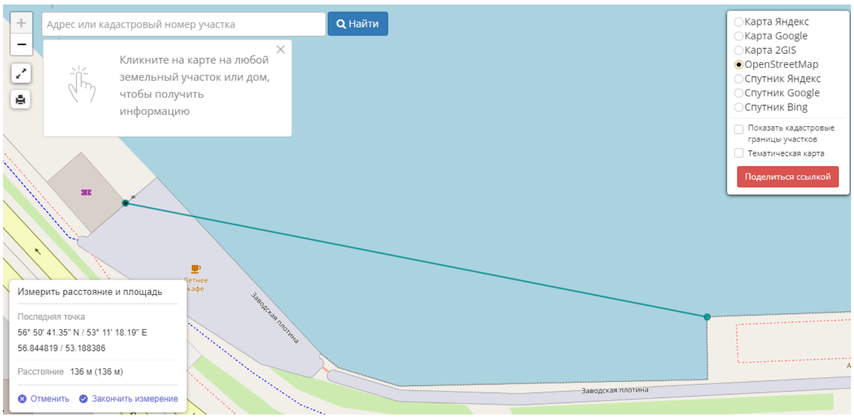

Fig. 1. Measurements on the public cadastral map

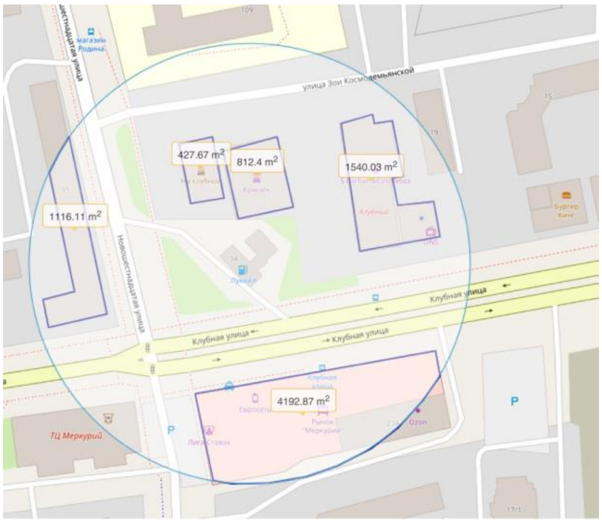

Fig. 2. Visual representation of the calculated zone, for the boundary of which the probabilities of consequences were determined

The next stage of the model experiment was the assessment of building density coefficient on the territory of the selected objects. A graphical representation of the measured areas is also shown in Fig. 2.

Building density coefficient ρ was determined by the formula:

$$\rho = \frac{\sum_1^n S_n}{S_{ref}}, \quad (1)$$

where n — the number of measured plots; S_n — the area of one measured plot, m^2; S_{ref} — the base area, m^2.

The area of a circle with a radius of 100 m was chosen as the base area. For all analyzed gas stations, the building density coefficient does not exceed the value of 26.7 %. It should be noted that this value does not include the area of green spaces such as shrubs or trees, which in summer to a certain extent perform barrier functions due to the presence of foliage, but in winter do not lead to a decrease in the impact of an air shock wave. With a density coefficient of 26.7 %, according to definitions [3], the situation can be characterized as slightly cluttered. In practice, it is necessary to take into account the building orientation in relation to the epicenter of the explosion and the material from which it is built. Out of seventeen initial objects, four were selected as meeting the research criteria. Further, on the basis of the measured values of distances to places of possible mass stay of people, the probabilities of occurrence of events — damaging factors of the explosion of the fuel-air mixture were determined. Table 2 provides the results of research and calculations.

Table 2

Results of calculations of the model experiment

No.	Coefficient of building density / calculation radius, m	Probabilities of damaging factors, %				
		Serious structural damage to buildings, P1	Complete destruction of buildings, P2	Probability of eardrum rupture, P3	Probability of survival as a result of pressure wave, P4	Lung damage, P5
1.	0/95	84	27.1	2.2	1.4	0
2.	13.2/60	23	2.9	0.7	0.6	0
3.	22.4/25	92.6	39.6	4.4	29.1	0
4.	26.7/60	87.6	31.7	2.9	23.6	0

Based on the analysis of the results obtained (Table 2), it can be stated that the probabilities of injury to people is at a sufficiently high level, while they can be reduced by special measures — the construction of barriers to the spread of negative explosion factors.

Discussion and Conclusion. As the study has showed, the prediction of the consequences of explosions of fuel-air mixtures can be justified by the presence of characteristic terrain features near gas stations with such fuels as gasoline, propane or methane. The terrain features, as a rule, consist in the fact that in the zone of significant consequences there may be places of mass stay or congestion of people, for example, public transport stops.

From the point of view of the completeness of consequences manifestation, two options are possible:

– there may be no barrier obstacles both in winter and in summer;

– the presence of green spaces in winter has a weak barrier effect in relation to the affected objects. Identification of such dangerous objects can be carried out with a comprehensive examination of the entire territory of the settlement.

It is proved that the measurement of building density can be defined as the ratio of the area of objects enclosed in a circle of the target diameter to the area of this circle. To conduct the study, the consequences of the explosion of fuel-air mixtures were calculated based on the probability function. This approach has proven itself on the positive side, including in international practice. It is able to give accurate predictive results with lower computational costs compared to computational procedures. The novelty implemented in the project is the use of the "Ruler" module, which allows you to estimate areas and linear distances on a geographical map of the area. This module allows you to determine the building density coefficient as the ratio of the sum of the areas to the area of a circle with a radius of 100 m, although you can choose distance. In this case, the center of the circle is the "conditional" middle of the gas station. In the best case, it is necessary to take into account the relative location of buildings or structures located near the target object, which can be either "longitudinal" or "transverse" to the epicenter.

According to the measurement results for the objects observed in the framework of this study, the coefficient of their building density does not exceed 26.7 %, which makes it possible to characterize the type of surrounding space as "open" or "slightly cluttered" in accordance with [3], and thus is confirmed quantitatively.

As the calculation results show, the probability of human survival in pressure wave for two of the four gas stations is at the level of 29.1 % and 23.6 %. The comparison with the maximum permissible values is not possible due to the lack of such. However, in relation to the acceptable probability, these values are significant. The acceptable probability can be calculated as the probability value of this criterion for the distance specified in method [3]. For liquid motor fuel filling stations with above-ground tanks located outside the territories of settlements, the minimum distances from them to such objects as places of mass gathering of people should be at least 50 m.

It is proposed to introduce the concept of "a place of gathering of people" as a place where 20 or more people can be at the same time. It is proposed that it should include public transport stops, regulated and unregulated crossings, including ground, underground, etc.

The accessibility and simplicity of the methodology with the use of open cartographic data makes it possible to carry out these types of calculations. The results of cartographic studies, along with computational procedures, have shown that currently there are those among gas stations that are characterized by the possibility of people crowding at close distances from them.

As the study has showed, the presence of conditions allowing the probability of explosions is quite common, although their implementation is episodic. Perhaps, their occurrence is due to historical reasons. The aforementioned public transport stops and similar temporary structures may not exist during the design and construction of gas stations, and may be installed by the decision of local administrations much later. The application of the proposed approach makes it possible to control their location and the level of risk from possible explosions at gas stations in a real situation.

Ultimately, the proposed approach to assessing the consequences of explosions of fuel-air mixtures allows you to quickly assess possible risks in real time and in accordance with the real situation in the area of the gas station location and plan specific measures to minimize them.

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