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SECURITY OF MAJOR PIPELINES IN PRESENCE OF TERRORISTIC THREATS: PROGNOSTIC ESTIMATES

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БЕЗОПАСНОСТЬ МАГИСТРАЛЬНЫХ ТРУБОПРОВОДОВ В УСЛОВИЯХ ТЕРРОРИСТИЧЕСКИХ УГРОЗ: ПРОГНОЗНЫЕ ОЦЕНКИ

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major pipelines, terroristic threats, unauthorized tie-in, physical security system, detection reliability, multi-sensor systems, vibroacoustic oscillations, leak detection, security zone, seismic oscillations, object protection costs, oil theft prevention problem, probability of errors of 1st and 2nd kind, economic damage, object security cost.

The purpose of the paper is to substantiate the approach to determining the required probability of detecting unauthorized attempts to contact the pipe shell to maintain a minimum level of pipeline security losses. That is also nesseccerly to assess probability trend in the near future. Based on the information obtained it is planned to propose the structure of the physical pipeline security system to neutralize terroristic attacks. Results of studies of vibroacoustic oscillations in the shell of a major pipeline during its operation are given. The mechanisms of change in parameters of a vibroacoustic pulse excited at a local point of a pipeline when it is propagated through a pipeline are expalined. Results of studies on the solution of the problem of detection and prevention of emergencies in the protected zone by seismic oscillations are considered. It is concluded that it is possible to detect precursors of emergencies by vibroacoustic and seismic vibrations of the pipe shell.
The effectiveness of the proposed approach to determine the requirements for systems of protection of objects from terroristic threats is demonstrated. The region was chosen in accordance with available published data for a relatively long period of time, necessary for setting up a computational experiment. It is interesting to receive prognostic estimates in that segment of economy for the country as a whole.
Presence of such information allow creating a policy for detecting terroristic attacks and deciding on the requirements for the physical protection system that have to be provided in the current period and short term.
Today, there is no way to effectively fight with prepared violators to achieve their goals using any of the known single-sensor systems.
It is concluded that there is a need to develop a multi-sensor system, minimum equipment of which should include interconnected seismic and vibro-acoustic subsystems. Combination of vibro-acoustic and seismoanalytical subsystems allows compensating the most significant drawbacks of each of them.

Ключевые слова:
магистральные трубопроводы, террористические угрозы, несанкционированные врезки, система физической защиты, надежность обнаружения, мультисенсорные системы, виброакустические колебания, обнаружение утечек, охранная зона, сейсмические колебания, затраты на защиту объекта, проблема предотвращения хищений нефти, вероятности ошибок 1-го и 2-го рода, экономический ущерб, затраты на защиту объекта.

Цель статьи – обосновать подход к определению требуемого значения вероятности обнаружения несанкционированных попыток контактировать с оболочкой трубы для поддержания минимального уровня потерь на охрану трубопровода, оценить тенденцию ее изменения в ближайшей перспективе и на основе этой информации предложить структуру системы физической защиты магистральных трубопроводов для нейтрализации террористических атак. Приведены результаты исследований виброакустических колебаний в оболочке трубы магистрального продуктопровода в процессе его эксплуатации. Дано объяснение механизмам изменения параметров виброакустического импульса, возбужденного в локальной точке трубопровода, при его распространении по трубопроводу. Рассмотрены результаты исследований по решению задачи обнаружения и предотвращения возникновений чрезвычайной ситуаций в охранной зоне по сейсмическим колебаниям. Сделан вывод о возможности обнаружения предвестников чрезвычайных ситуаций по виброакустическим и сейсмическим колебаниям оболочки трубы.
Продемонстрирована эффективность предложенного подхода по определению требований к системам защиты объектов от террористических угроз. Выбор региона определился наличием опубликованных данных, охватывающих сравнительно протяженный период, необходимых для постановки вычислительного эксперимента. Представляет интерес получать прогнозные оценки в этом сегменте экономики для страны в целом.
Наличие такой информации позволит сформировать политику по обнаружению террористических атак и определиться с требованиями к системе физической защиты, которые необходимо обеспечить в текущий период и в ближайшей перспективе.
На сегодняшний день не просматривается возможность эффективного противодействия подготовленным нарушителям по достижению поставленных ими целей с помощью любых из известных односенсорных систем.
Сделан вывод о необходимости разработки мультисенсорной системы, минимальная комплектация которой должна включать взаимосвязанные сейсмическую и виброакустическую подсистемы. Комбинация виброакустической и сейсмоаналитической подсистем позволяет компенсировать наиболее значимые недостатки каждой из них.

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Introduction

Detection of unauthorized tie-ins and prevention oil theft from pipelines are the most relevant and complex problems in operation of main pipelines [1]. Over the past 5 years in the territory of the Russian Federation almost 5.000 unauthorized tie-ins have been identified. That represents 70 % of all crimes related to the theft of oil and its products. One in four of these tie-ins was found in the territory of Samara region [2]. According to a president of Transneft, there were in 2014 in the regions of the Russian Federation 320 criminal incidents identified in the main pipelines, 385 tie-ins in 2015 and 238 tie-ins for 10 months in 2016 [3].

Criminal interventions in the operation of the main pipelines pose the greatest threat to the environment, as they cause spills of oil and its products, pollution of soil, rivers and reservoirs.

The problem of criminal tie-ins and theft of oil from the main oil pipelines is viewed by experts as a serious multifactor threat to Russia's national security. According to the data obtained by the author [4], the share of all accidents for this reason is 69 % of all accidents.

Analysis of annual reports on the activities of the Federal Service for Environmental, Technological and Nuclear Supervision for 2010–2016 [5] indicates that the number of accidents on the main pipelines are decreasing over time (Fig. 1).

According to official data of Rostekhnadzor, annual economic damage to enterprises from accidents at the main pipeline transport facilities is estimated as hundreds of millions of rubles [5] (Fig. 2).

The authors of [6] carried out an analysis of publications on ensuring the safety of pipeline transport and detection of unauthorized work in the

Fig. 1. Dynamics of accidents on the main pipelines of Russia from 2010 to 2016

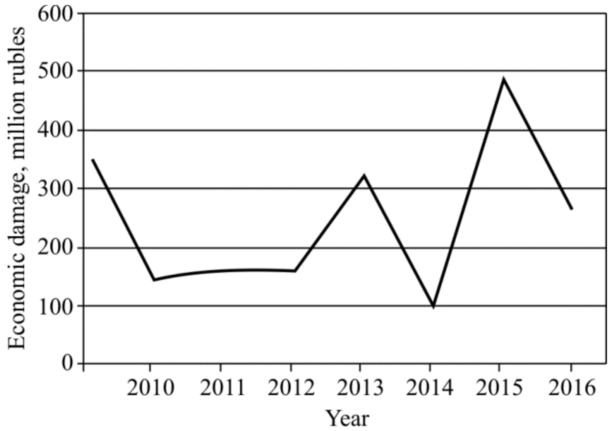

Fig. 2. Economic damage for enterprises from accidents on the main pipelines from 2007 to 2016

guard zone of the monitoring facility. The analysis showed that the research are mainly focused on creating a system of physical protection of the main pipelines that implements the principle "not to miss the contact of the attacker with the pipe shell".

In the paper [6] the authors indicate that over the past few years a significant number of publications on this subject have been presented in international databases. So, there are more than 80 publications in the Web of Science database and 60 publications in Scopus. The analysis of RISC database publications over the last 5 years (2012–2016) indicates that there is an interest renewed among the scientists in the problem of ensuring the safety of pipeline transport and the detection of unauthorized tie-ins over 90 (Fig. 3).

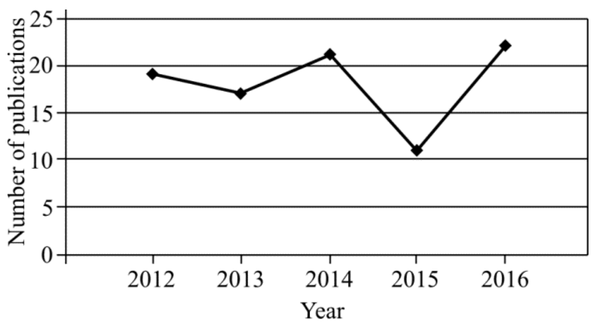

Fig. 3. Dynamics of the publication activity in the RISC database on the problem of ensuring the safety of pipeline transport and detection of unauthorized work in the guard zone of the monitoring facility from 2012 to 2016

Therefore, at the present stage of development of pipeline transport of oil and oil products, the issue of ensuring reliable and fail-safe operation of main pipelines.

There is a number of studies aimed to solve the problem of detection and prevention the emergencies in the protection zone by seismic fluctuations [7–9]. Improving the parameters of video analytics system to detect suspicious activity of subjects in the zone of control is declared by the patent [10]. It is proposed to carry out exploration of small leaks of the pumped product using thermal imaging systems installed on air vehicles [11]. The possibility of using thermal imaging systems for detecting product leaks and camouflaged excavation sites was considered in [12, 13]. The transfer characteristic of the transmission path of vibro-acoustic signals formed in the pipeline envelope is determined by a number of factors, including the state of soil adjacent to it. This circumstance is used to detect product leaks and excavations in the area of the monitored facility [14–17]. In some cases, video analytics systems are used to allow one to trace the behavior of the subject(s) in the guard zone of the monitoring object [18, 19].

The greatest interest is shown in the investigation of a fiber-optic cable for the detection of unauthorized work in the pipeline security zone [20, 21]. Seismic vibrations cause deformation of the cable, their intensity in any place is determined by the optical signals reflected from the heterogeneities. Suppression of accompanying noise is considered to be the the main problem of fiber-optic technology in the current period. Nonstationary fluctuations in seismic fields reduce the reliability of detection of signals from objects. The problem of obtaining reasonable estimates for probabilities of identifying event types in the analysis of processes recorded from optical fiber processes is discussed in [22]. However, it is truly noted in [23] that there is no reliable data on the satisfactory operation of such systems on extended objects (over 10 km). The paper presents the results of tests of the domestic system Danube. Its ability to detect the movement of heavy equipment and develop of soil by a mechanical method in the zone of sensitivity of the fiber-optic cable is proved. The detection zone of heavy equipment was 100–150 m and 50–100 m for mechanical soil development. The sensitivity depends on a number of factors: depth of the cable laying, type of the cable, type of soil and its condition (dry, wet, frozen), type of event, distance to the reflectometer. Since surface acoustic waves reach the cable, the optimum depth of cable laying is 30–40 cm.

There is a conclusion made in [24] about the need for R&D, as well as the development of data processing techniques to further improve the technology. The feature of the study is that there is no description in required details of conditions for carrying out the experiments and estimates obtained for the probabilities of errors of the first and second kind. There is also no information on the operability of the systems under investigation in the presence of artificially created interference by the attackers. There is no reasonable data on reliability of intrusion detection of persons in the pipeline security zone and classifications of their actions. Directive assessments like "... the minimum time to false alarm ... should not be less than 170 hours (1 week), good immunity is characterized by $T_{f.a} \geq 720$ h (1 month)" [25] do not have a serious evidence base ($T_{f.a}$ – duration of the interval of 1st false alarm).

A problem statement

In accordance with system laws, the process of improving the technology for solving specific problems is first characterized by the fastest rate of increase in its parameters. Then there is a slowdown in growth and sharp increase in costs to ensure an insignificant increase in these parameters. There is an evolutionary law of technology development, described by an S-shaped curve.

The possibilities of improving the methods of detecting and recognizing images obey the same pattern. After the attainment of certain values of the probabilities of errors of the 1st and 2nd kind, their further insignificant decrease is associated with such a massive increase in the necessary resources. That looses its meaning in realization of the intention. It is necessary to use a new method or combination of the old and new ones.

Fig. 4 shows the graphs reflecting the loss of the owner of the object during its operation, depending on the probability of detecting terrorist attacks P_a [26]. The less money is invested in ensuring the security of the infrastructure created, the greater losses that can be expected when it is used. The minimum point of total loss determines the required probability of detecting attacks.

Improving the one-sensor systems to increase the probability of R_a at the last stage of the "*S*-shaped" development is associated with high costs. There are limits to improvement: the opposing side invents new methods of attacking.

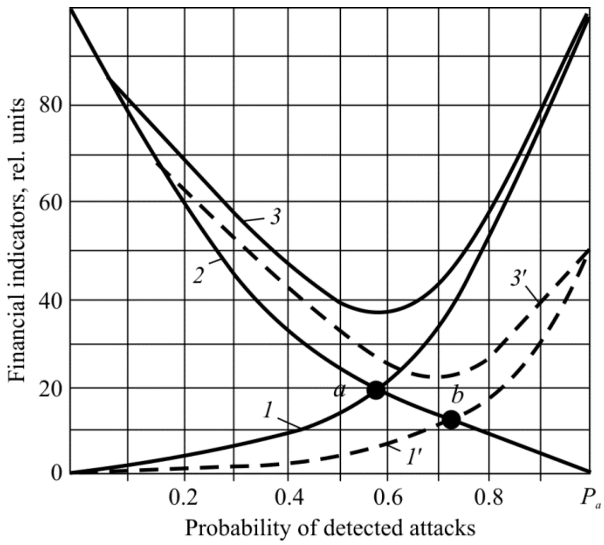

Fig. 4. Financial indicators of the parties' confrontation depending on the likelihood of detecting attacks P_a: *1* (*1'*) – protection costs when using single-sensor (*1*) and multi-sensor (*1'*) systems; *2* – damage from missed attacks; *3* (*3'*) – total losses of the owner of the object when using the single-sensor (*3*) and multisensor (*3'*) systems with points *a*, *b*

This circumstance stimulates the development of multisensor systems (curves *1'* and *3'* in Fig. 4 reflect their ability to reduce costs).

The owner of the object knows the costs of its protection and losses from missed attacks. It is possible to estimate on them the direction of improvement of the counteraction system for ensuring the optimal value P_a.

Position and shape of the curves given in Fig. 4 are limitation of the approach described. The curves reflect the expenditure items depend on many factors, the dynamics of their change exceeds the real possibilities for modernizing the systems to counter threats.

It is necessary to have predictive information about the intensity of terrorist activities and conditions for conducting it in the short term, in order to take into account these data when developing technologies for the purpose in question. The approach for obtaining such the information is developed in the paper.

Theoretical analysis

A generalized model that allows solving the posed problem can be represented as

$$\frac{dN_1}{dt}=\left[f_1\left(\text{GDP},\ \frac{\text{I}}{\text{C}}\right)-f_2\left(\frac{\text{MH}_{90}}{\text{MH}_t}\right)-\frac{\alpha_1\beta_1}{\alpha_2\beta_2}\cdot yN_2\right]\cdot N_1(t);$$
$$\frac{dN_2}{dt}=\left[f_3\left(\frac{\text{PC}}{\text{L}}\right)-f_4\left(\frac{\text{S}}{\text{I}}\right)+\frac{\alpha_2\beta_2}{\alpha_1\beta_1}\cdot yN_1\right]\cdot N_2(t), \qquad (1)$$

where N_1 – the number of attacks on the protected object; GDP – the gross domestic product per capita in the past year; I/S – the ratio of average income from the transaction to the cost of its conduction; $\text{MH}_{90}/\text{MH}_t$ – the ratio of the moral health of the population of the country (region), respectively, in the 90th and current years; α_1, β_1 – levels of qualification and technical equipment of the attacking party; α_2, β_2 – levels of qualifications and technical equipment of defenders; S – salaries of defenders; γ – the coefficient of interaction of defenders and attackers, which are inversely related to the size/extent/area of the protected object; N_2 – the number of defenders of the object; C – costs for object protection, L – total losses from attacks on the protected object.

The GDP characterizes the poverty of society, the function f_1 (GDP = const, D/R) characterizes the proportion of the population willing to commit an offense depending on the expected income and having sufficient knowledge to commit a crime in the sphere of activity in question. Obviously, in case of (I/S) ≤ 1 function value f_1(GDP = const, I/S) = 1 (there is no sense in carrying out the operation without getting any profit; the factor of "revenge" is not taken into account). The curve f_1(GDP = const, I/S) has a saturation region, when the resource of members capable of committing an offense of a given kind is exhausted. For communities characterized by a different ratio of limiting factors, the shape of the curve is preserved but its coefficients change:

$$f_1(\text{GDP} = \text{const, I/S}) =$$
$$= a_1 / (1 + b_1 \exp(-c_1\ \text{I / S})),$$

where a_1 – the coefficient that determines the part of society potentially ready to move to the camp of offenders from selfish interests. Coefficients a_1, b_1, c_1 are determined by expert technologies taking into account the GDP received in the previous year.

The function f_2 ($\text{MH}_{90}/\text{MH}_t$) = ($\text{MH}_{90}/\text{MH}_t$) f_1(I/S) characterizes the lawfulness of the population, its cultural level and legislative framework for combating the relevant type of crime. MH_t acts as an integrated indicator, estimated from the state statistics (on indicators that characterize the social tension in society). Functions f_3, f_4 are special cases of logistic curves.

Obviously, the higher the N_2 the higher the cost of protecting the object of ST. Total losses from attacks L increase with the number of attacks, i.e. with growth of N_1. One of the possible variants of the function f_3 (ST, P, N_1, N_2), taking into account its logistic characteris

$$f_3=\frac{a_3\exp\left(\dfrac{\text{L}N_1}{\text{PC}\cdot N_2}b_3-c_3\right)}{\left(1+\exp\left(\dfrac{\text{L}N_1}{\text{PC}\cdot N_2}b_3-c_3\right)\right)},$$

where a_3, b_3, c_3 – curve shape factors.

Assessment of the state of protection and its difference from the optimal (equal protection costs and losses from attacks on the object) is made using the value of registered $dN_1(t)/dt$, current expenditures for protection of the facility and losses from attacks on it, D/P value determined by the survey of the population of the adjacent territories and the tracked ratio $\text{MH}_{90}/\text{MH}_t$. This assessment determines the requirements for probability of detection of attacks and false alarms, which should be provided by the security service of the facility.

A particular case arising from the model (1) and reflecting the interaction in the "terrorist-defense system of the main product pipeline-police" system can be represented as a system of four equations [27]:

$$\begin{aligned}
&\frac{dN_L}{dt} = r_{L0}\left(1 - \frac{N_L}{N_{L0}N_{L\max}}\right)N_L - \\
&\quad - \alpha_L P_a m_L P_M N_L N_M + r_{L2};\\
&\frac{dN_B}{dt} = \alpha_L\left(\frac{N_L}{g_L} - N_L\right) - \frac{N_L}{g_L}P_a\alpha_L;\\
&\frac{dN}{dt} = r_{s0}\left(\frac{D_B(-t_s)}{b_B D_0}\right)^{k_{s1}} - r_{s1}\left(\frac{D_s}{b_s D_B(-t_s)}\right)^{k_{s2}};\\
&\frac{dN_M}{dt} = \frac{N_L(-t_M)}{g_L}P_B(-t_M)\alpha_L r_{M0} - \\
&\quad - r_{M1}N_M + r_{M2}N_L,
\end{aligned} \tag{2}$$

where $N_L(t)$ – the number of terrorist attacks at time t; N_B – the number of attacks on the object; N_p – the number of pipeline protection elements; N_M – the number of police officers, involved in the investigation of criminal activities on the main pipelines; r_{L0} – expansion coefficient of information between members of society ("viral" factor) [28]; N_{Lm} – the capacity of the environment in which the "idea of product theft" will spread into [29]; α_L – the average number of terrorist group yields per object of attack per unit time; P_a – likelihood of attack detection; m_L – probability of detaining terrorists; P_M – probability of conviction of detained terrorists; r_{L2} – coefficient of increase in the number of adherents of the idea of product theft; g_L – average size of a group of terrorists; r_{s0}, r_{s1} – coefficients of increase and decrease in costs for the protection of the object; k_{s0}, k_{s1} – the protection strategy factors that determine the limiting values of the missed attack probability and false decisions of the object protection system used; D_B – casualty losses t_s; D_s – object protection costs; b_B – loss of the share of income from the operation of the facility as a result of the attack; b_s – the ratio of losses from attacks to costs of object protection; t_M – the delay in responding police structures to a registered attack; r_{M0}, r_{M1} – respectively, the growth rate and reduction in the number of police officers involved in investigating the facts of attacks on the protected object; r_{M2} – the coefficient of growth of police officers in case of change in theft activities.

Computational experiment

The computational experiment was carried out on the example of Samara region in connection with availability of published data covering a relatively long period of time. There are on the territory of Samara region 24 main oil pipelines and 4 oil pipelines with a length of about 4 thousand km, operated by organizations of the system "Transneft" (Privolzhsnefteprovod – 1.837 thousand km, Northwest MN OJSC – 965 km, Druzhba oil pipeline – 538 km, 2 subsidiaries of Transnefteproduct – South-West Transnefteprodukt – 366 km and Uraltrans-nefteprodukt – 228 km). On average, over 310 million tons of oil and oil products are pumped through the territory of Samara region over the year.

Theft of oil in Samara region took a significant scale. According to the pipeline security officer, in the early 2000s there was no empty space on the map of Samara region pipelines, where the red dots denoted the tie-ins to the pipe. About 1 million tons of oil was stolen in one year only. There 44 tie-ins were recorded in 2010. Then, after Transneft installed control systems, the scale of oil theft was reduced [30], and in 2011 23 tie-ins were recorded. By 2012, the number of reports in the media about tie-ins to oil pipelines was increased sharply. The largest number of reports occurred in the Irkutsk, Leningrad, Samara regions.

In 2012 Samara region became the all-Russian leader in the number of criminal tie-ins to main pipelines. In 2012, according to Transneft, 34 criminal encroachments on trunk pipelines were recorded in Samara region. In all regions at that time the number of frames was reduced. In Samara region it grew by 67.4 %. Since the beginning of 2013 in the Samara region, 55 illegal taps in oil pipelines and 26 in main pipelines have been identified. Following the results of 2013, the Samara region took the first place in Russia in terms of theft of oil from the main pipelines.

From 2003 to 2013 almost a quarter of criminal tie-ins to the pipeline system were detected in the region from the total number of frames detected in Russia, in particular 1651 unauthorized tie-ins. But in 2014 the number of unauthorized cuts in main oil pipelines dropped to 17. According to [31], there were 32 unauthorized taps revealed in the main pipelines in 2015 and 24 cases in pipelines by October 2016.

The adequacy of the model (2) is verified by comparing the simulation results of the “mortal terrorism” process in Samara region with the real data presented in the published materials for the period from 2010 to 2016.

Long-term projections based on the model in question predict a new cycle of significant growth in terrorist attacks on main pipelines, with a subsequent decline by the end of the third decade (Fig. 5).

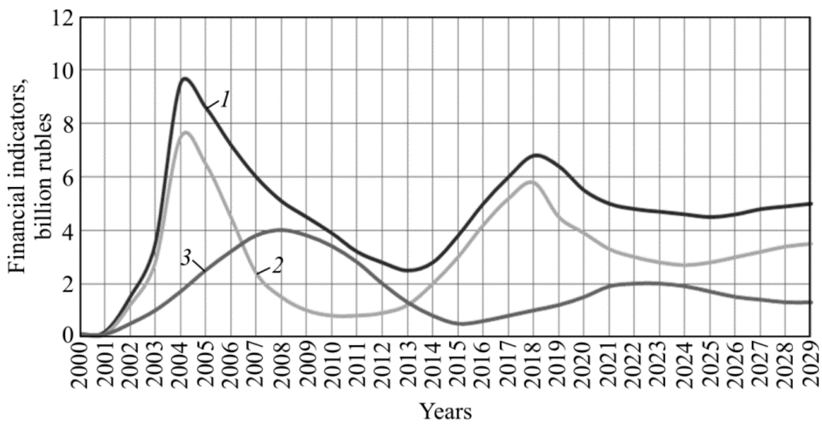

Fig. 5. Forecast of financial indicators of the parties' confrontation until 2029, while maintaining the current level of probability of detection of attacks by defense systems: *1* – annual total costs, billion rubles; *2* – annual damage from frames, billion rubles; *3* – annual protection costs, billion rubles

Information about the actual costs of protection and the size of losses from the frames is of a closed nature. Therefore, the data given in Fig. 5 reflect trends in the costs of protection and damage from product theft with the figures taken at the initial time (2000). Other indicators of the model correspond to those established for the Samara region at the same time.

Results and discussions. Conclusions

The model (2) allows to estimate the required probability of detection of attacks P_a. The results of modeling one of the scenarios for countering terrorist attacks (see Fig. 5) allow to conclude that the most favorable moment in 2013 was observed in organizing the protection of pipeline transport. From this point of view, it would be necessary to increase the costs of protecting the facilities in order to prevent the growth of total costs in the short term.

The effectiveness of the approach proposed to determine the requirements for systems to protect objects from terrorist threats is demonstrated in the example of the Samara region. The region was chosen by the availability of published data covering a relatively long period of time necessary for setting up a computational experiment. It is of interest to receive projections in this segment of the economy for the country as a whole.

The availability of such information will make it possible to formulate a policy for detecting terrorist attacks and determine the requirements for the physical protection system that must be provided in the current period and in the short term.

Today, there is no way to effectively counter prepared violators to achieve their goals using any of the known single-sensor systems. It is necessary to determine the composition of multi-sensory systems. The combination of vibro-acoustic and seismo-analytical subsystems allows to compensate the most significant drawbacks of each of them.

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