Structure of the physical protection system of main pipelines from deliberate threats

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Abstract. Statistics of emergency situations at pipeline transport facilities indicate that there are problematic issues in the products transportation. The accidents of the past decade were dominated by the theft of these products ("mortem terrorism"), sabotage acts also were recorded. The main direction of research to counteract these threats is aimed at detecting disturbances in the seismic field in the pipeline security zone using a fiber-optic cable (sensor). In the article we propose the structure of the physical protection system of main pipelines to detect and neutralize unauthorized tie-ins into the pipe in order to minimize the level of pipeline protection losses.

1. Introduction
Pipeline transportation is one of the safest, most reliable and efficient methods of continuous transportation of the unlimited flow of products over long distances regardless of the weather. The total length of pipelines in Russia is about 285 thousand km by 2018. However, the statistics of emergency situations at pipeline transport facilities indicate that there are problematic issues in the transportation of oil, oil products and gas. Pipelines start to fail as they age, leaks appear. Personnel errors have begun to play an important role along with the traditional causes of emergency situations: corrosion, natural impacts, etc (table 1) [1].

| Country (region) | External influences, % | Equipment defects, % | Corrosion, % | Natural impacts, % | Personnel errors, % | Others, % |
|------------------|------------------------|----------------------|--------------|-------------------|---------------------|----------|
| Russia           | 63(17)                 | 19(30)               | 6(50)        | – (–)             | 12(3)               | – (–)    |
| The USA          | 23(25)                 | 20(19)               | 23(23)       | 4(10)             | 7(2)                | 23(21)   |
| Western Europe   | 37(50)                 | 25(16)               | 28(15)       | 3(7)              | 7(5)                | – (7)    |

There are other reasons that lead to leakage - accidental damage to the pipeline, terrorist acts, sabotage, unauthorized tie-in with the aim of stealing the product, etc. One of the most critical and complex problems in the operation of main pipelines is the detection of unauthorized tie-ins and the prevention of oil theft from pipelines. In recent years, one of the main causes of accidents at oil pipelines in Russia are unauthorized tie-ins and sabotage (69.1%), as a result of which oil spills occur, pipeline tightness is violated, which leads to a reduction in their service life, significant economic damage, preconditions for environmental catastrophes.
Over the past 5 years, almost 5000 unauthorized tie-ins have been found on the territory of Russia, which accounts for 70% of all crimes related to the theft of oil and its products. According to the “Transneft” CEO, 320 criminal incidents were detected on main pipelines in the regions of the Russian Federation in 2014, 385 tie-ins in 2015, 238 unauthorized tie-ins for 10 months in 2016.

Criminal interventions in the operation of main pipelines pose a huge threat to the environment, as they are the cause of accidents, spills of oil and oil products, pollution of soil, rivers and reservoirs [2].

The structure of the accidents of the past decade was dominated by the theft of these products, "mortem terrorism", "identified 4779 thousand tie-ins in main pipes" [6], documented acts of sabotage. In the country "during transportation, up to 5% of black gold is plundered, up to a quarter in the North Caucasus" [3].

The total number of accidents registered in the data bases is 4019 in the USA at 2015, and 502 in Russia.

The press secretary of Greenpeace Russia indicated in its publication (February 2018) that more than 10 million barrels of oil are spilled annually in Russia. This is twice as much as during the Gulf of Mexico disaster.

In the 21st century, pipeline transport is worn-out by 50-70%. According to the estimates of EMERCOM specialists, more than 20% of the main pipelines and more than 40% of oilfield pipelines are over 30 years old, although the accident-free period of use is 10-20 years.

Accidents lead to leaks of oil products, gas from pipelines, which poses a serious threat to people, the environment, and cause huge economic and environmental damage, lead to environmental pollution[4].

The main cause of accidents on the main gas pipelines in the US is a defect in equipment (27%) and corrosion of pipes (24%). For Russia's main gas pipelines, accidents are caused by corrosion of pipes – 49%, equipment defects – 32%. The main cause of accidents on the oil pipelines for the last decade is external impact - 60% of cases, while in the USA it is only 20%.

The authors [5] carried out an analysis of the publication activity in the field of ensuring the safety of pipeline transport and the detection of unauthorized actions in the protected zone. The analysis showed that the research is mainly focused on creating a physical protection system for main pipelines, which implements the principle: "Do not miss the contact of the attacker with the pipe shell". The authors of [5] found that a significant number of publications on this subject have been submitted in international databases over the past few years. There are more than 80 publications in the Web of Science database and more than 60 publications in Scopus. The analysis of the publications in the RINC database over the last 5 years (2012-2016) indicates renewed interest to the problem of ensuring the safety of pipeline transport and the detection of unauthorized frames among the scientists. There are more than 90 publications.

The results of the investigations in the field of detection product leaks from oil and gas pipelines are summarized in [6, 7]. It can be stated that the main interest of foreign researchers is concentrated on the development of seismic (57%), optical (23%) and vibro-acoustic (14%) methods of detection and prevention of product leaks. In seismic methods, the main direction is the improvement of signal processing algorithms (~ 58%), 27% of publications are devoted to the analysis of the possibilities of various sensors, the remaining 15% can be attributed to the description of detection objects and test results of the proposed systems.

Considerable attention is paid to the use of a fiber-optic cable as a sensor for measuring the distribution of temperature and mechanical stresses in the surrounding pipeline environment. Local inhomogeneities of these parameters lead to the appearance of Raman scattering components propagating along the optical cable (Raman, Mandel'shtam-Brillouin, etc.). The location of these inhomogeneities is judged by the time of propagation of these components from the place of scattering (the principle of active radar) [8-10]. Fiber-optic sensors for the oil and gas industry are produced by Weatherford, Baker Hughes, Halliburton, Schlumberger, as well as Russian companies Omega, Optolink, Intel-Systems. The stated principle of detection of external influences on the surrounding pipeline environment (mechanical stresses) and leaks (local changes in the ambient temperature) is the
basis for the Omega leak detection and activity control system developed by JSC “Transneft”, which analyzes changes in the temperature field in real time and detects gas, oil and other liquids leaks in multiphase pipelines up to within 5 meters [11]. Another similar security fiber-optic system "Danube", which has undergone numerous field tests at the facilities of OOO Gazprom, allows to record the movement of a person and manual digging directly above the cable. When a person or a car approaches a protected object, the system captures and transmits information about it with an accuracy of 10 meters to the operator's computer. Based on the test results of the foreign systems used to detect terrorist attacks on long objects, it can be concluded that all issues related to the possibility of solving the problem under consideration have been removed from the agenda [9,12]. However, there continues to be confusion with the efficiency of these systems in the presence of noise of natural and artificial origin. This circumstance, apparently, was taken into account by the authors of the latest publications, which came to the following conclusions:

- "reliable data on the satisfactory operation of such systems on extended objects (over 10 km) have not been found in the open press";
- "it is necessary to conduct additional research and develop a data processing technique to further improve the method";
- "Fiber-optic methods for detecting leaks in pipelines require serious modifications. In complex seismically active conditions, there is a need for combination with heat and vibration methods".

2. The noise factor
A sign of a terrorist attack is the invasion of the intruder into the protected zone and the formation of a pit for contact with the shell of the pipe. In the place of deformation of the soil, seismic oscillations are formed, which, upon reaching the fiber-optic cable, causes its deformation. In the upper layer of the soil, the velocity of longitudinal waves and the coefficient of absorption are proportional to the square root of the oscillation frequency. Depending on water saturation, porosity, etc. the speed of these waves can differ by more than 10 times. Because of these reasons the shape of the recorded disturbances can vary considerably during the day. This circumstance makes it difficult to apply optimal methods for detecting these disturbances against the background noise. Amplitudes of natural seismic noise are at the level of 1 μm and are commensurable to the amplitude of signals (Figure 1).
This circumstance determined the conclusions of the form: "... the analysis of data from a distributed fiber-optic sensor is hampered by a huge level of interference". Methods of accumulation and filtration are used to counter interference. Wavelet filtering is the most widely used, allowing to reduce the noise level in all frequency bands. Most foreign research is focused on the development of this direction.

In [13] it is asserted that the detection of Raman scattering signals against the background of nonstationary random processes proved to be ineffective. The use of wavelet noise purification allowed to increase the signal-to-noise ratio by 11 dB. The work [14] is devoted to the control of environmental noise, which affects the indicators of phase-sensitive reflectometry (phi-OTDR) in the detection and localization of dynamic excitations. It is claimed that by using the "specific" spectral analysis the probability of correct detection can be brought up to 94%, and the level of false alarms - up to 6%. Are these figures acceptable to the consumer?

The existing approach to assess the required indicators of security systems is formed on the basis of expert technologies. Probability of correct detection is 0.8; 0.9; 0.97 are recognized as low, medium and high "signaling" reliability. As to the noise immunity of the method, one false alarm for 100 hours or less in a 250 m section is not considered satisfactory. In this case, the flow of false alarms in a 2.5 km section exceeds the border beyond which the security service ceases to react to them. High noise immunity is considered to be a false alarm for 1300-2500 hours on a site served by a separate security group. The published figures on the noise immunity of the monitoring systems for the state of main pipelines do not reflect this aspect of the problem, and there is a need to eliminate this gap.

It is advisable to solve this issue not with the use of expert technologies, but relying on the principle of minimizing the amount of losses from terrorist attacks and the costs of protecting the facility.

Another feature of ensuring the safety of pipeline transport appears because of the need to take into account that we are dealing with a "well" organized groups who generously spend money on bribing the right people, training their "specialists", buying special means to actively counteract the police and the security service ...". The technology of concealing the stolen product by pumping water into the pipeline in a volume equal to that taken is one of the examples of the "invention" of the attacking party. There are many proposals for masking the vibroacoustic signals in the patent and periodical literature. The industry produces a wide range of vibration generators for these purposes. The installation of such a generator under a layer of soil in the buffer zone, which forms seismic signals "excavations", creates serious problems for the security services. Other options for solving the problem prepared by the attacker are addressed in [15]. One way of solving it is considered below.

3. Multisensory system of ensuring safety of trunk pipelines in the conditions of terrorist threats
In the field of the protection of critical facilities, there is a list of rules that should be followed when designing physical systems to ensure their security [15]. One of them: if the detection system does not solve the problem with the required reliability, it is necessary to combine the means with different physical principles to respond to the attacker. A combination of 2, 3 interacting systems should be used to counteract the person prepared for the "business". If two of them are characterized by the detection probabilities $P_1$ and $P_2$, the final probability is

$$P_0 = P_1 + P_2 (1 - P_1).$$

At $P_1 = P_2 = 0.8; P_0 = 0.96$. This rule is widely used abroad when designing so-called multi-sensor perimeter protection systems [16]. In addition to distributed fiber-optic systems for the preventive neutralization of terrorist threats to extended objects, the capabilities of video-vibroanalytical and thermal imaging systems were evaluated.

Video analytics refers to the technology of computer analysis of video data in order to make a decision about the state of the object of observation without human participation. The results achieved to date: when using a camera with a resolution of 640x480 pixels, observations can be made in a territory up to 200 m in lengths under snowing weather conditions with an intensity of up to 0.5 mm / h and wind speeds up to 8 m / s on dynamic natural backgrounds. Estimates of the probabilities of missed targets and false alarms when detecting an intruder were $0.041 \pm 0.003$ and $0.003 \pm 0.001$, respectively [17].

The vibroanalytical method is based on the generation of elastic vibrations in the shell of the pipe with subsequent analysis of the recorded signals, at a given distance from the generation cross section. When waves propagate through the shell of a buried pipeline because of the significant difference in the wave impedances of the metal and gas, the reradiation of the energy of the propagating signal into the pumped product is negligible (at a normal incidence of the longitudinal wave on the "steel-air" (air-steel) boundary, only 0.002% energy, but a significant proportion of it goes to the surrounding soil). Due to the leakage of energy into the pumped liquid, the damping of the propagating oscillations in their shell will be greater than in the gas pipelines (about 12% of the vibration energy and the same order passes through the "water-steel" boundary to the surrounding soil). When the parameters of soils in the local area (oil yield, soil removal, etc.) change, local reradiation of the energy of the signal propagating along the shell is formed. In [17], a conclusion was made about the potential for pipe state detection by analyzing the form of the recorded signal, the result of accumulation of 180,000 "ping" pulses, and demonstrated this possibility in an experiment when the system tried to find an ammunition installed on the pipe, a pit above the pipe, etc. It was shown in [18] that the local change in physical parameters in the space near pipe is better detected by increasing the energy of the "ping" signals, rather than by changing their shape. The "generator-receiver" module allows controlling pipeline sections with a length of 2 km and more. To generate elastic waves in the shell of the tube, piezoceramic generators are widely used in the form of flexible surface linings of various shapes.

The underground pipelines diagnostics technology from aircrafts using thermal radiation is considered in [19]. Even small cracks in the pipes lead to the appearance of thermal anomalies on the surface of the ground, allowing localization of the leak location by an unmanned aerial vehicle. Estimates are obtained for the density of false solutions in the detection of hidden objects of different shapes on the pipeline route. A sharp decrease in the cost of air monitoring when using unmanned aerial vehicles (10 times or more compared to the use of helicopters) put this technology in the perspective position. Experiments on the detection of leaks from pipelines in the thermal range of optical radiation are described in [20, etc.]. The creation of a 3D thermal model of thermal fields over a buried pipeline is nearing completion, interest in the use of which was shown by JSC "Transneft". Also, the question was raised about the need to ensure a qualitatively new level of reliability of oil pipelines and oil product pipelines in the face of terrorist threats. OAO AK "Transneft" aims to "create integrated security systems that can be managed from a single center".
The creation of complex multisensory systems is based on the use of the Saati hierarchy analysis method. Taking into account the specific nature of the problem under consideration, it is necessary to have specific data of the social and economic situation and the "moral" health of the population in the country in the current period and in the immediate future. However, in the simplest version of the solution of this problem, we can confine ourselves to the following example.

Figure 2 illustrates the losses incurred by the owner of the pipeline system from attacks by the opposing side. The less money it invests in ensuring the security of the created infrastructure, the greater losses should be expected when it is used. Pa (required probability of detection) is determined by the minimum total loss point. The owner of the object knows the costs of its protection and losses from missed attacks. Using them, one can assess the direction of improvement of the counteraction system to ensure the optimal value of this probability. However, one should keep in mind the dependence of the position and shape of the curves in Figure 2, reflecting spending items, from many factors, the dynamics of their change exceeds the ability to modernize existing systems to counter threats in accordance with the requirements of the current situation [2].

The analysis of publications over the past decade suggests that the technology for detecting activity in the security zone, implemented using a distributed fiber-optic sensor, will be used as a basis for ensuring the safety of main pipelines from terrorist threats in the near future. Therefore, care should be taken to neutralize false decisions, especially in conditions of creating artificial interference in the protected zone.

Currently, a view has been formed to complement fiber-optic systems to detect unauthorized access by one of the subsystems outlined above. Within the multi-sensor system, the requirements for each of the subsystems are adjusted. In accordance with the recommendations in [9], the length of an individual link based on a fiber-optic sensor should be about 40 km. The detector based on it is designed to provide a high probability of correct detection, including through increased false solutions. The task of the system interacting with it is to check which of the incoming solutions is correct, and to weed out the wrong ones.

4. Conclusion
The above-mentioned video analytics, vibroacoustic and thermal imaging systems can be used for this purpose in the form of various combinations of interaction with the base detector and with each other. The simplest combination: "fiber-optic channel - vibroanalytical channel - security service." For each link of the first type, at least 10 links of the second type are required. The energy costs for the work of the vibroanalytical link are near 0.5 J. Therefore, it is included in the work after receiving signals of "attacker appearance "from the first link. If the density of false decisions from the fiber optic detection system is ≤ 1 h⁻¹, the problem of energy efficiency of a multi-sensor system of this kind is removed. Taking into account that according to the theoretical analysis the probability of false decisions of the
second link (the sign of removing part of the ground in the environment of the pipeline) tends to zero, then as time goes on creating the pit, the system will satisfy the reliability of detection.

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