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Original article

Ensuring Safety of Gas Field Infrastructure Using ALARP and a Systematic Approach

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Abstract

Introduction. A significant part of the global and state economy is the production and supply of hydrocarbon raw materials. The issues of safety in this area will remain important in the coming decades. The problem is actively discussed in the professional and scientific community. Theoretical and applied works are published. Local, point-based methods are calculated and implemented, which allow predicting and preventing emergencies in certain units of the considered objects. At the same time, there are no sufficiently justified and reproducible system solutions that can take into account the state of, for example, oil or gas field as a single complex and act as indicators not only of ordinary local accidents, but also of systemic accidents — catastrophes. Such a scientifically and experimentally based solution is described in this article. The approach is proposed as part of the formation of a comprehensive scientific and technical program (CSTP) to ensure the safety of natural and technogenic objects (NTO). The aim of this work was to describe the practice of its application in the conditions of specific gas fields and to justify the refusal to focus on solutions that took into account only the minimum practically acceptable risk, that is, built on the ALARP principle (as low as reasonably practicable).

Materials and Methods. The article was based on the results of field tests of natural and technogenic objects (NTO) of the oil and gas complex — the Yuzhno-Russkoye field of OJSC Severneftegazprom (SNGP), LLC Gazprom Dobycha Yamburg (GDYA) and the gas pumping station (GPS) Orlovka-2 (Ukraine), conducted with the authors' participation. Significant results were obtained and evidence-based physically interpreted during acceptance tests of an explosion-proof certified, created under the guidance of the authors of a prototype of a disaster response system (DRS) at the integrated gas treatment plant (IGTP) in LLC GDYA in 2006. At the same time, for the first time in the world practice, the fact of early detection and parrying without consequences by means of DRS on the UKPG-2 of the development of a large-scale general industrial disaster was confirmed.

In the form of graphs, the revealed patterns of NTO have been visualized, which made it possible to form harbingers of the development of accidents and catastrophes at the NTO of LLC "GDYA", SNGP and GPS "Orlovka-2". Information on the high experimental reproducibility of the obtained results was presented.

The technology has been developed of early detection and parrying of all types of potentially dangerous self-exciting systemic phenomena on real NTO infrastructure — self-oscillations. Three cases of their excitation in real gas fields were presented.

Results. The paper shows the fragmentary nature and locality of emergency protection systems based on the ALARP principle. The consequence of this was its complete unsuitability for early detection and counteraction to the most large-scale and costly system accidents — catastrophes that were multifactorial processes, in which none of the factors was decisive. The alternative complex solution of the problem proposed by the authors and brought to working condition was based on a system approach adapted to the NTO of the oil and gas complex.

The measured parameters of various NTO infrastructure — fields of LLC "GDYA" and SNGP were processed and analyzed at the moments of development of self-oscillating modes on them, due to self-sustaining nonlinear mechanisms of interaction of NTO elements with constant (non-oscillatory) sources of energy replenishment. Three such modes of self-excitation were illustrated. The most informative in this case were the transient modes of operation of the equipment.

According to the technologies experimentally developed by the authors, the areas of critical operating modes of equipment with pronounced potentially dangerous bifurcation points were analyzed. The result of superimposing treatments of the measured parameters of eight full-scale tests of NTO — graphs of dimensionless amplitude-frequency characteristics of the interconnections of a real dynamic system was presented: "input — gas cooling housing" → "output — pipe casing" at the frequency of self-oscillations.

Discussion and Conclusion. The capabilities of ALARP did not meet the tasks of system monitoring of the occurrence and development of dangerous incidents in gas fields. This conclusion can be attributed to all standard sizes of NTO infrastructure in Russia. Fundamentally different solutions should be used to ensure comprehensive observability, controllability, and safety of NTO. A comprehensive scientific and technical program is recommended: "Innovative hardware and software tools and technologies to ensure the observability, controllability, and safety of the NTO infrastructure of Russia".

Keywords: natural-technogenic object, ALARP principle, safety of oil and gas fields, development of a system accident, counteraction to the development of accidents

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Научная статья

Обеспечение безопасности инфраструктуры газовых месторождений средствами ALARP и системного подхода

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Аннотация
Введение. Значимую часть мировой и государственной экономики составляет добыча и поставка углеводородного сырья. Актуальность вопросов безопасности в этой сфере сохранится в течение ближайших десятилетий. Проблема активно обсуждается в профессиональном и научном сообществе. Публикуются теоретические и прикладные работы. Просчитываются и внедряются локальные, точечные методы, которые позволяют предсказывать и предупреждать аварийные ситуации в определенных узлах рассматриваемых объектов. При этом нет достаточно обоснованных и воспроизводимых системных решений, способных учитывать состояние, например, нефтяного или газового промысла как единого комплекса и выступать индикаторами не только обычных локальных аварий, но и системных аварий — катастроф. Такое научно и экспериментально обоснованное решение описано в представленной статье. Подход предложен в рамках формирования комплексной научно-технической программы (КНТП) обеспечения безопасности природно-техногенных объектов (ПТО). Цель работы — описать практику его применения в условиях конкретных газовых промыслов и обосновать отказ от ориентации на решения, учитывающие только минимальный практически приемлемый риск, то есть построенные по принципу ALARP (англ. as low as reasonably practicable).

Материалы и методы. Исходными для статьи стали результаты проведенных с участием авторов натурных испытаний природно-техногенных объектов (ПТО) нефтегазового комплекса — Южно-Русского месторождения ОАО «Севернефтегазпром» (СНГП), ООО «Газпром добыча Ямбург» («ГДЯ») и газоперекачивающей станции (ГПА) «Орловка-2» (Украина). Значимые результаты получены и доказательно физически интерпретированы при приемо-сдаточных испытаниях сертифицированного на взрывобезопасность, созданного под руководством авторов прототипа системы противодействия развитию катастроф (СПРК) на установке комплексной подготовки газа (УКПГ) в ООО «ГДЯ в 2006 году. При этом впервые в мировой практике был актирован факт раннего обнаружения и парирования без последствий средствами СПРК на УКПГ-2 развития масштабной общепромысловой катастрофы.

В виде графиков визуализированы выявленные закономерности ПТО, позволившие сформировать предвестники развития аварий и катастроф на ПТО ООО «ГДЯ», СНГП и ГПС «Орловка-2». Представлена информация о высокой экспериментальной воспроизводимости полученных результатов.
Отработана технология раннего обнаружения и парирования всех типов потенциально опасных самовозбуждающихся системных явлений на реальных ПТО инфраструктуры — автоколебаний. Представлены три случая их возбуждения на реальных газовых промыслах.
Результаты исследования. Показана фрагментарность и локальность систем аварийной защиты ПТО, базирующихся на принципе ALARP. Следствием этого стала его полная непригодность для раннего обнаружения и противодействия самоорганизованно возбуждающимся наиболее масштабным и затратным системным авариям — катастрофам, представляющим собой процессы многофакторные, ни один из факторов в которых не является определяющим. Предложенное авторами и доведенное до рабочего состояния альтернативное комплексное решение проблемы базируется на адаптированном к ПТО нефтегазового комплекса системном подходе.
Обработаны и проанализированы измеряемые параметры разных ПТО инфраструктуры — промыслов ООО «ГДЯ» и СНГП в моменты развития на них автоколебательных режимов, обусловленных самоподдерживающимися нелинейными механизмами взаимодействия элементов ПТО с постоянными (не колебательными) источниками восполнения энергии. Проиллюстрировано три таких режима самовозбуждения. Наиболее информативными при этом оказались переходные режимы работы оборудования.
По экспериментально отработанным авторами технологиям были проанализированы области критических режимов работы оборудования с выраженными потенциально опасными точками бифуркации. Представлен результат наложения обработок измеряемых параметров восьми натурных испытаний ПТО — графиков безразмерных амплитудно-частотных характеристик взаимосвязей реальной динамической системы: «вход — корпус охлаждения газа» → «выход — трубная обвязка корпуса» на частоте автоколебаний.
Обсуждение и заключение. Возможности ALARP не отвечают задачам системного мониторинга возникновения и развития опасных инцидентов на газовых месторождениях. Этот вывод можно отнести ко всем типоразмерам ПТО инфраструктуры России. Для обеспечения комплексной наблюдаемости, управляемости, безопасности и защищенности ПТО следует задействовать принципиально иные решения. Рекомендована комплексная научно-техническая программа: «Инновационные программно-аппаратные средства и технологии в обеспечение наблюдаемости, управляемости, безопасности ПТО инфраструктуры России».

Ключевые слова: природно-техногенный объект, принцип ALARP, безопасность нефтегазовых промыслов, развитие системной аварии. противодействие развитию аварий

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Introduction. According to the Center for Research on the Epidemiology of Disasters (CRED), almost all large-scale system accidents are recorded post factum. This indicates a significant amount of work and efforts that are needed to ensure safety of natural and man-made facilities [1]. It should be emphasized that in this case, safety is a systemic (integral) nonlinear quality of a complex system. Scientific research in this area involves, in particular, the revision of stable stereotypes. One of them is the statement that the parts determine the properties of the entire object (including safety). It should be recognized that this theoretical approach (in some cases justified) does not find practical confirmation when it comes to the problems considered in the framework of this study. Not only the risks of epidemics and man-made disasters are growing in the world, but also the implementation of the worst scenarios and the enormous losses associated with them. The experience of recent years proves an extremely low awareness of the features of such processes and the inability to influence them.

The first full-fledged emergency protection systems in the world practice were created in Russia in the 50s and 60s of the last century. Their authors were specialists in rocket space engines. In the 1970s and 2010s, as part of the conversion, civil industries were able to use these unique achievements to solve safety problems of complex general technical infrastructure facilities. First of all, the developments were used at nuclear and thermal power facilities, in the oil and gas complex, and aviation. In the circumstances concerned in 1995, on the initiative of the NPO Energomash named after V.P. Glushko, the authors of the presented article formed an interdepartmental working group of the Russian Academy of Sciences. In 2014, it was legalized by the decision of the All-Russian Research Institute for Civil Defense and Emergency Situations of the Ministry of Emergency Situations of Russia (Federal Center for Science and High Technologies).

The group took part in the works listed below.

1. In 2006, for the first time in world practice, a system was created that was certified for explosion safety and allowed to counteract the development of a real large-scale industrial disaster.

2. In 2016, a Strategy for countering the development of disasters was developed and defended.

3. In 2017, on behalf of the President of the Russian Academy of Sciences, the strategy "Innovative technologies and means of protection against man-made accidents at industrial infrastructure facilities in Russia" was formed, scientifically and experimentally substantiated, and defended.

4. In 2021, a Comprehensive Scientific and Technical Project (CSTP) of the full innovation cycle "Innovative software and hardware and technologies to ensure the observability, controllability, and safety of the NTO infrastructure of Russia" was created, scientifically and experimentally substantiated, and defended.

We should emphasize that the formulation of the problem and the technologies focused on its solution were the result of work first on the Concept (on the instructions of the leadership of the All-Russian Research Institute for Civil Defense and Emergency Situations of the Ministry of Emergency Situations of Russia), and then on the Strategy of the Russian Federation to counter the development of Disasters (by the decision of the Presidium of the Russian Academy of Sciences).

From the point of view of safety, one of the essential non-linearities of complex multicomponent infrastructure objects is a violation of the superposition principle. The fact is that the safety of the NTO is not determined by the state and functioning of its constituent elements[1, 2, 3, 4].

Nevertheless, in the real conditions of NTO operation, the world practice remains, as it was 100 years ago, traditional, that is, locally oriented. It is based on the erroneous principle that the NTO is safe if all its elements are safe. This is due to the almost complete loss of control of man-made disasters, which on average are 4–5 orders of magnitude more costly in terms of consequences compared to local accidents in the NTO elements. Only in recent decades it has been possible to understand, scientifically and experimentally substantiate the physical mechanisms governing such incidents [1–4].

It should be noted that an application is ready for the development of a full innovation cycle CSTP "Creation of innovative software and hardware and technologies to ensure the observability, controllability and safety of natural and man-made infrastructure facilities in Russia". The project is focused on the creation of breakthrough domestic technologies to increase the competitiveness of the economy in compliance with the provisions of the basic documents of Russia's strategic development. The application has been approved for submission to the Council for Priority Areas of Scientific and Technological Development of the Russian Federation. As a result, within the framework of the all-Russian strategy, a unified system of natural and man-made security (USNMS) of the infrastructure of Russia will be created [1, 5, 6].

The aim of the work was to describe a new practice implemented in the conditions of a specific gas field and to justify the refusal to focus on solutions that take into account only the minimum practically acceptable risk, that is, built on the principle of ALARP (as low as reasonably practicable). Let us clarify that the promising, global goal of the authors' scientific and applied research, including those described in this article, was to create, within the framework of the Strategy of the Russian Federation, an object-oriented unified system of natural and man-made security (USNMS) of the infrastructure of Russia, an alternative output according to the ALARP ideology.

According to Rostekhnadzor of the Russian Federation, during the transportation of liquid and gaseous hydrocarbons, cases of local accidents at regularly operated enterprises numbered in the hundreds and thousands cases. In particular, there were:

– 545 cases of depressurization on the main pipelines during the last decade of the XX century;

– 42 thousand cases of depressurization on the infield pipelines during 2001 alone.

[1] Decree of the President of the Russian Federation of December 31, 2015 No. 683 "On the National Security Strategy of the Russian Federation". URL: https://www.consultant.ru/document/cons_doc_LAW_191669/ (accessed: 02.11.2023). (In Russ.).

[2] Decree of the President of the Russian Federation No. 642 of December 01, 2016 "On the Strategy of Scientific and Technological Development of the Russian Federation". URL: http://kremlin.ru/acts/bank/41449 (accessed: 02.11.2023). (In Russ.).

[3] Consolidated strategy for the development of the manufacturing industry of the Russian Federation until 2024 and for the period up to 2035. Approved by Decree of the Government of the Russian Federation No. 1512-r of June 6, 2020.URL: http://government.ru/docs/39844/ (accessed: 02.11.2023). (In Russ.).

[4] Idem.

Obviously, only large-scale and costly organized counteraction could solve the problem.

The world's first successful practice was implemented in Russia in the 50–60s of the XX century in the field of safety of heavy-duty liquid-propellant rocket engines for space purposes during development and routine fire tests [5]. It is known as the emergency protection system (EPS).

In the 80s, a similar emergency shutdown system (ESS) was created in the West for general technical facilities. It was based on the ALARP principle [6–9], which has been repeatedly refined in Russia and its numerous Russian versions[5] [8–10]. Let us note that the term ALARP originated in the 70s in the field of British legislation on health and safety at work, that is, outside the systematic approach. As a result, it retained many characteristic features of that time, but exhausted them.

At the same time, safety policy of oil and gas production and transportation according to the ALARP principle more often concerned the procedures for optimizing work processes. This practice was less often applied to the actual emergency protection due to the weaker scientific and experimental elaboration of issues related to the relevant processes.

Materials and Methods. The research focused on the problem of creating an EPS production chain of oil and gas production and transportation based on the ALARP principle [11–13]. It accompanied the project of creating the USNMS NTO, therefore, a comparative analysis of both approaches was carried out in the work.

As a rule, safety problems were solved by the interaction of:

– the customer (consumer of output products);

– the contractor (ideologist, developer and manufacturer of output products);

– the parties involved in the creation of NTO (design organizations and enterprises implementing projects).

In general, the object of research was an open dissipative dynamic system that combined elements that were interdependent and interacted with each other and with the external environment. Two complementary information components were taken into account to ensure safety of such NTOs:

– elements in the NTO (local accidents);

– NTO as a whole (a complex of interrelated elements, local accidents and systemic disasters).

A mandatory stage of such work was the coordination of the customer's request and the contractor's capabilities.

Each component was a set of processes with its own energy and indication.

Results. It should be emphasized that the study of the NTO elements in itself was not informative enough to understand its state as a whole [3–4]. The observability, controllability and safety of the NTO as a system were not determined by the characteristics of its constituent elements, even if all of them were taken into account.

Thus, according to ALARP, the most common cause of accidents and technological disasters was the human factor. This does not correspond to the modern point of view [3]. Nevertheless, the ALARP principle has become even more widespread in Russia than in the UK. In particular, it was recommended by GOST for risk management[6].

The current situation does not negate doubts about the validity of ALARP. Below are its statements that have caused explicit or implicit limitations for qualitative research on the NTO safety.

1. NTO elements do not interact with each other or their interaction can be neglected. This contradicts the real state of affairs. All NTO infrastructures, including oil and gas complexes, are multicomponent, complex dynamic systems. They are viable only with a controlled interaction of elements. That is, the fallacy of the statement is easily refuted by practice. Why is it not abandoned? The fact is that such an approach justifies simplifying the procedure for summing up the risks of the NTO elements in order to obtain an integral risk for the whole object.

2. The only material carriers and sources of danger to the NTO infrastructure are the elements that form them. The statement is true, but only in relation to local type accidents. The rule does not work if we are talking about system accidents — catastrophes that are more expensive than the local ones by an average of 4–5 orders of magnitude. Catastrophes are multifactorial phenomena. These are the consequences of violations of the normal dynamic interaction of the NTO elements with each other, NTO with its own control system, NTO with adjacent equipment, NTO with the external environment, etc.

3. The sources of danger in the NTO elements are statistically mutually independent. This assumption is wrong, first of all, in relation to the most severe system accidents — catastrophes that arise due to violations of the interaction of the NTO elements.

[5] GOST R IEC 61511-3-2011. Functional safety. Safety instrumented systems for the process industry sector. Part 3. Guidelines for the determination of the required safety integrity levels. URL: https://docs.cntd.ru/document/1200094220 (accessed: 02.11.2023). (In Russ.).

[6] GOST R 54505-2011. Functional safety. Risk management on railway transport. URL: https://docs.cntd.ru/document/1200094215 (accessed: 02.11.2023). (In Russ.).

4. The risk associated with the element has been taken as a measure of the element's danger. Other, more significant risks caused by violations of the interaction of elements with each other and with the external environment of the NTO are not taken into account. The measure of the NTO danger as a functional unit is determined by the sum of risks of its elements [6–11], [14]. It is unacceptable to summarize the risks associated with the NTO elements. And the point is not that they usually have different dimensions (with the help of the matrix apparatus of risks, the dimension can be excluded [14]), but in the statistical interdependence of the sources of the danger of NTO. According to the ALARP scenario, there is no way out of this situation.

As a result, it is necessary to operate with understated risk indicators compared to their actual values, which means underestimating the real dangers for NTO.

The above allows us to make a number of statements.

– ALARP suggests following an outdated local approach to solving safety problems of the NTO infrastructure, which limits the scope of its application. The situation is aggravated by the failure to mention the unsuitability of ALARP for solving problems of system analysis of the state and behavior of the NTO infrastructure.

– Specialists focused on working on ALARP do not have special tools for the study of the NTO infrastructure itself, the development of elements and in general EPS, as well as for the maintenance of the output result of ALARP, etc. Let us note that such tools are planned to be developed within the framework of the previously mentioned CSTP.

– ALARP specialists do not have a technology that can adequately provide the required informativeness, manageability and safety of the NTO.

– Equipping the NTO infrastructure with emergency protection systems based on ALARP does not meet the modern vision on the problem of ensuring the safety of NTO.

Thus, the main weakness of ALARP is the refusal to take into account the dynamic interaction of elements as part of the NTO infrastructure.

Experimental confirmations of the extreme importance of the dynamic interaction of the NTO elements of oil and gas fields. The authors of the presented article take the opposite position and have repeatedly received confirmation of its validity when conducting research and development work, including conversion, designed to ensure man-made safety of civilian facilities, taking into account the experience of space engine building. One of these civilian areas has become the extraction and transportation of oil and gas. It is important to note that the authors had unique specialized hardware and software resources and technologies (including of their own development).

Some results of full-scale tests of different standard sizes of NTO were obtained for the first time. To convey these results and the accumulated experience, the evidence-based data on the decisive role of the processes of interaction of the NTO elements are presented below. They are necessary for the formation of informative components of the NTO work processes, and can also be harbingers of large-scale, often spontaneously developing anomalies such as man-made disasters [1, 3]. In the real conditions of geographically distributed oil and gas fields, the interactions of elements were traced over distances:

– about 10 m at the facility safety levels;

– up to 100 m at the workshop levels;

– up to 10 km at the field level.

The authors did not conduct research at larger distances between the elements.

Let us list the constructs of the production links of oil and gas production and transportation, which form the dynamic interactions of the elements of the technical control system:

– energy producing units (combustion chambers, gas generators, cylinders of internal combustion engines, etc.);

– energy converters (pumps, compressors, turbine units);

– external and internal bindings of workshops interacting with other links, by-passes, input and output manifolds;

– energy storage links;

– wellheads.

Figures 3–7 in the article are the results of the analysis of the measured parameters of various NTOs infrastructure, which were investigated by the Interdepartmental Working Group of the Russian Academy of Sciences represented by the authors during field tests.

Let us start with the most common regular systemic phenomena in the oil and gas industry — self-oscillations caused by self-sustaining nonlinear mechanisms of the interaction of the NTO elements with constant (non-oscillatory) sources of energy replenishment. In the cases described below, the results from the authors' own experience of conducting field tests of oil and gas facilities were used, although the coverage was significantly wider and included thermal power plants, hydroelectric power stations, nuclear power plants, production and operation of heavy-duty diesel generators, turbo-expanding assemblies (TEA), etc.

The main attention was paid to the timely detected incidents, which, thanks to the use of technical means, did not develop into accidents and catastrophes. Thus, at the Yuzhno-Russian field of OJSC Severneftegazprom, when fixing a powerful self-oscillating process of the dynamic interaction of the pair "ground structure of the well cluster → adjacent subsurface", an emergency shutdown of the existing well cluster was triggered (Fig. 1).

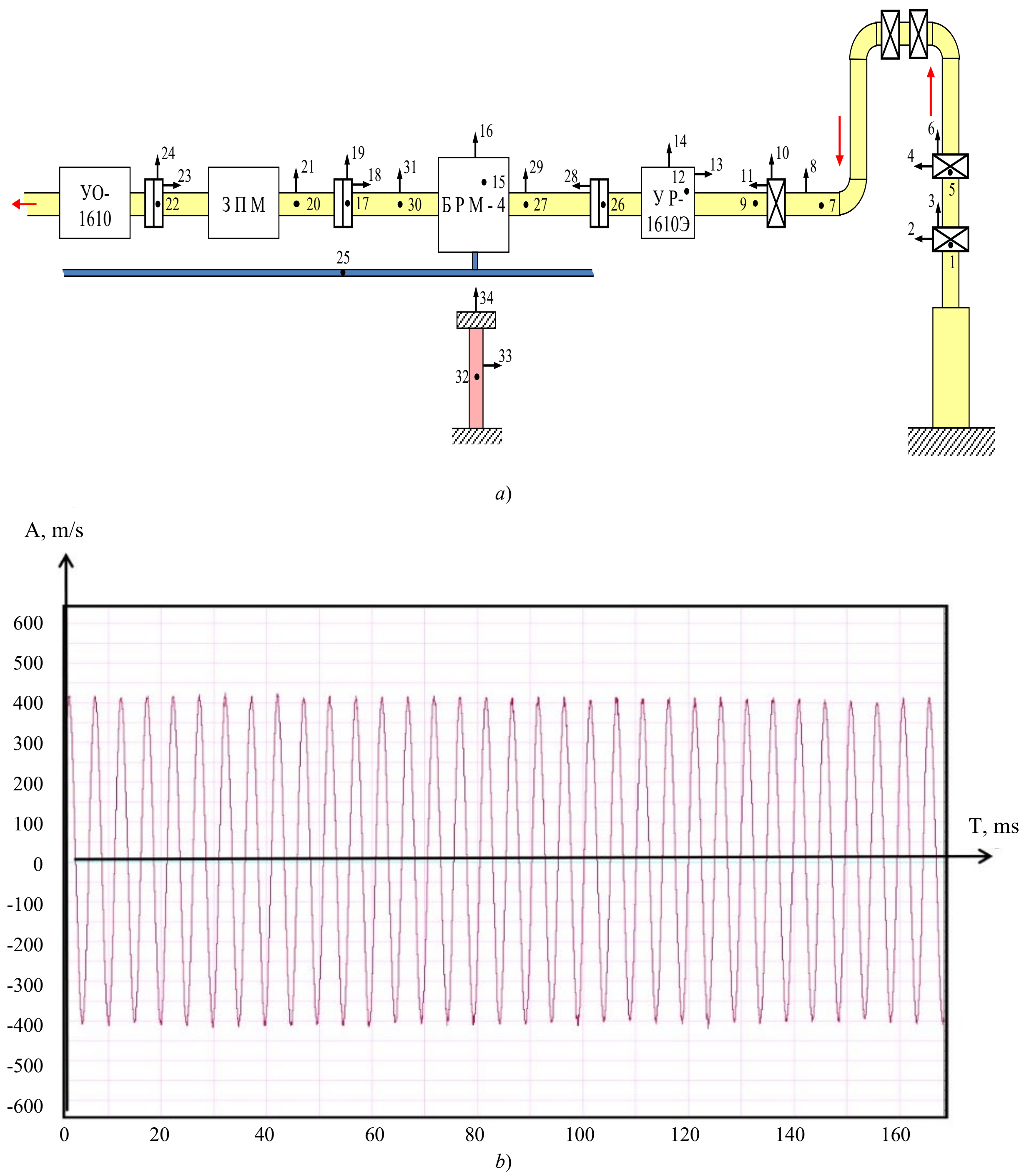

Fig. 1. Self-oscillating process of the dynamic interaction of the pair "ground structure of the well cluster → adjacent subsurface ", recorded at the Yuzhno-Russian field of OJSC Severneftegazprom: *a* — wellhead; *b* — fragment of the vibration parameter of the pipe head of the wellhead at the initial moment of self-excitation of powerful natural and man-made self-oscillations with a frequency of ≈ 200 Hz

Let us explain that part a) presents the design of the wellhead with a 34-channel system for measuring and recording vibration parameters of the 2nd string of the 9th well cluster. The black arrows show the locations of the sensors and the measurement directions of the vibration parameters of the structure of the 2nd string of the 9th well cluster, the red arrows show the direction of movement of the gas flow. Here, УО is a shut-off device, ИБ is a measuring unit, БРМ is a methanol control unit, and УР is a regulating device.

The authors of the article had to urgently distract themselves from their main work and take part in clarifying the nature of the dangerous phenomenon. As the subsequent calculation and analysis of metal from critical sections showed, the fatigue strength of the metal structure was exhausted in the next 2–2.5 hours.

Additional processing of the measurement results made it possible to establish dislocations of:

– a constant source of energy replenishment (adjacent bowels of the cluster of wells);

– a nonlinear oscillatory circuit (cluster of wells).

The authors have worked out the appropriate methodology, software and hardware in relation to space propulsion. At the frequency of excitation of self-oscillations of all pairs of measured vibration parameters of the wellhead, coherence almost coincided with unity.

Figures 2 and 3 present the location and characteristics of the case of self-excitation of self-oscillations. The authors recorded it when they conducted full-scale tests of the integrated gas treatment plant (IGTP) at Gazprom Dobycha Yamburg LLC (GDYA) in the frequency range of 36-56 Hz (depended on the operating mode).

The physical mechanism was identified as self-oscillation — a strong dynamic interaction of the gas drying housing equipment and its external strapping. The most informative tests turned out to be on transient modes of operation of the equipment:

– slow throttling from 100% of the mode to 65% (in time from 550 seconds to 750 seconds);

– slow subsequent forcing from 65% of the mode to 85% (in time from 1200 seconds to 1300 seconds).

Fig. 2. At the integrated gas treatment plant (IGTP-2), a strong nonlinear interaction of dynamic links occurred "gas drying body (on the right, in the background) → external binding"

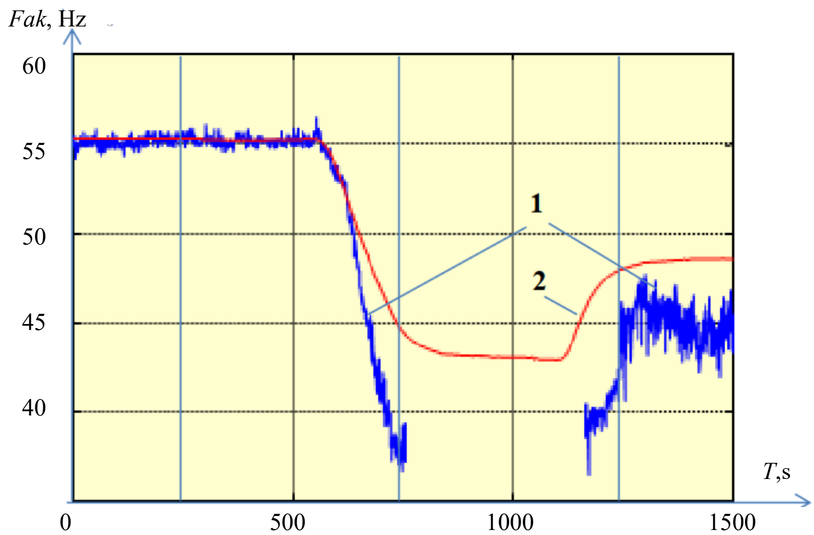

Fig. 3. IGTP-2. Time dependence of the frequency of self-oscillatory interaction of dynamic links "gas drying body → its external binding": 1 — according to the processing of the results of field tests; 2 — according to the accompanying theoretical calculation

The acceptance tests of the explosion-proof prototype of the disaster response system (DRS) at the GDYA IGTP-2 in 2006 turned out to be unique in terms of information content and practical physical interpretation of the discovered phenomenon. To confirm the experimental reproducibility of the results, 10 similar full-scale tests of IGTP were planned in the modes of regular forcing and throttling. The only non-rigid exception, as expected, was the 8th test. Let us note that complex systems had different time scales. In the 8th case, in order to obtain a higher time resolution than in the previous seven tests, the process gradient was reduced by more than half.

Due to the exceptional importance of the test results, in addition to regular measurements, the program regulated the deployment of a 96-channel geographically distributed system for measuring various parameters of the facility. At the automated workplace of the DRS operator in the gas drying building, the parameters were presented after group synchronization and centralization (GPS satellite system was used).

Pronounced bifurcation points in the working processes of the production field (at ≈ 18% of the nominal value) attracted the attention of the authors long before the acceptance tests. However, this phenomenon had not previously caused incidents, so the tests were not canceled. Figure 4 shows the result of graphs overlay of eight of the planned ten DRS tests.

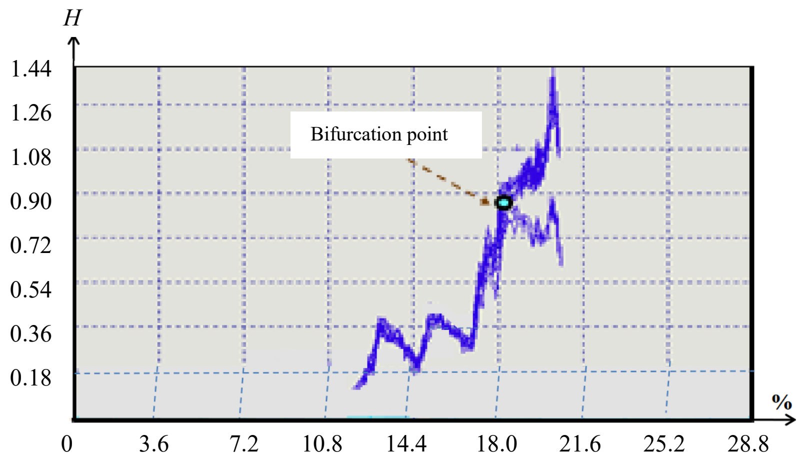

Fig. 4. IGTP-2. The result of eight full-scale tests overlay— graphs of dimensionless amplitude-frequency characteristics and relationships of the dynamic system: "inlet — gas cooling housing" → "outlet — pipe casing" at the frequency of self-oscillations

Here, in the forcing sections, after passing the bifurcation points, the lower branch of the curve was used in tests 1, 3, 4, 6, and the upper branch was used in tests 2, 5, 7, 8.

It is clear that the blurriness of the graph in Figure 4 (as well as the graphs in Figures 6, 7 and 8 for other objects) is explained not by errors in measuring the NTO parameters, but by overlays of the results of processing data from field tests conducted at the same values of the operating parameters of each object. At the same time, the blurriness of the graphs is important from the point of view of informativeness. It makes it possible to:

– clearly present the degree of reproducibility of test results (or other parameters, depending on the formulation of the problem), that is, to draw conclusions about the correctness or incorrectness of the problem being solved;

– take reasonable tolerances for the tasks of making decisions about technical and (or) functional state of the NTO in the forms of dependence on the operating parameters of the NTO in the entire range or sub-ranges of values.

Figure 5 shows a fragment of the processing of the results of the eighth test in the vicinity of the critical point (18% of the nominal value) at the throttling site with the spontaneous development of a systemic technogenic accident. At that time, there was no gas automation in the cooling and drying housing, so the situation was adjusted manually using a bypass. They did not use a conventional emergency stop, but reverse forcing.

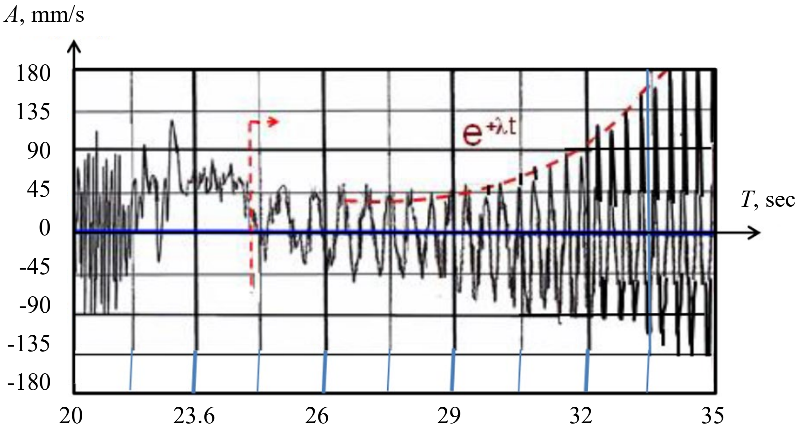

Fig. 5. IGTP-2. The initial stage of spontaneous development of a systemic disaster

Experimentally determined post factum, the horizon of the disaster forecast turned out to be unprecedentedly large — $\tau^* = 90$ sec at the values of Lyapunov exponents in the areas of excitation and damping of oscillations, respectively: $\lambda_1 = +\ 0.14$ Hz and $\lambda_2 = -0.38$ Hz. We have established the reason for such a rare phenomenon in the NTO operation. It is due to the discovered (apparently for the first time in world practice) mechanism of a two-stage scenario of excitation and development of a catastrophe. At the first step of the previously established critical mode with the bifurcation point shown in Figure 4, there was a shop system excitation of a group of production field elements — turbo expander units in interaction with an external pipe binding. It also played the role of a trigger mechanism in the second step, which was characterized by a strong interaction of the wellheads with the subsurface.

Subsequently, the development of this general industrial disaster was qualified as the first in the world practice to detect in time (which made it possible to take countermeasures) an extremely dangerous regional man-made natural earthquake with a magnitude of 6 to 7 points on the Richter scale. The energy source was the subsoil, the constructs of the clusters of wells worked as a trigger mechanism. A decisive role was played by manually lowering the throttling gradient at the eighth acceptance test and, accordingly, increasing the production field time in the danger zone — in the vicinity of the critical bifurcation point at ≈ 18% of the nominal value.

Now it has become a universal practice to detach resonant frequencies from dislocation zones or to accelerate their overcoming in transient modes. Examples include space rocket engines, nuclear power plants, hydroelectric power plants, aviation equipment, etc.

Two factors realized during the acceptance tests are of exceptional importance.

1. A systematic approach to the organization and conduct of DRS tests. Formation of a package of initial experimental data to understand the essence of the mechanism and counteract the development of an extremely dangerous phenomenon — a general industrial disaster, which geographically and in time coincided with a man-made natural earthquake. The local approach peculiar to ALARP and its output products was not in demand in this case.

2. High information content. The standard system for measuring production field parameters has been supplemented. A geographically distributed parameter measurement system with group synchronization and centralization of parameters was used. The regularly measured production field parameters indicated the development of an emergency:

– a fraction of a second before its completion, when emergency protection was impossible;

– only by secondary signs in the high-frequency range (the main events were recorded at low frequencies).

Figure 6 shows overlays of the results of processing of twelve full-scale tests of turbo-expanding units in the gas drying housing of IGTP-2 LLC GDYA during one and a half months of repair.

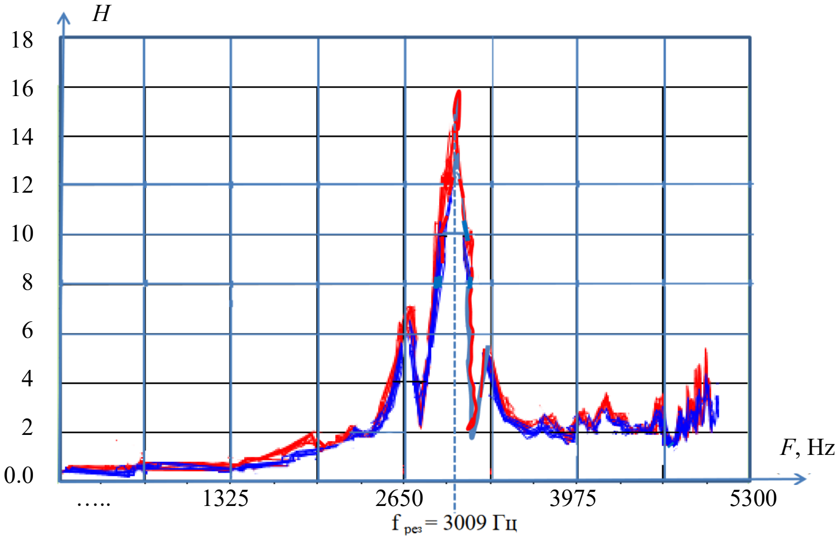

Fig. 6. Experimentally reproducible amplitude-frequency characteristics of the dynamic system "TEA-2 → TEA-7"

In this case, the authors used a two-channel modular unit for high-precision synchronous isolation of frequency components $53F_p$ (53 — the number of turbine blades of the studied standard size of turbo-expanding assemblies) in the axial vibration parameters of TEA-2 and TEA-7 turbines. The modes of slow forcing (red curves) and throttling (blue curves) of TEA-2 operated. The work was carried out in the nominal normal mode of TEA-7.

Thus, the amplitude-frequency characteristics of the resonant type (Fрез = 3009 Hz) of the potentially dangerous high-quality ($Q \approx 76.5$) dynamic interaction of TEA-2 and TEA-7, reproduced in a wide frequency range up to 5300 Hz, were evident. It was necessary to develop and implement serious counteraction measures. In addition, additional field tests were conducted to confirm their effectiveness. This was a unique case of experimentally reproducible system testing of TEA-2 in the modes of starts and stops of its dynamic interaction with an adjacent, operating at the nominal mode TEA-7 in a wide frequency range. This experimentally proven approach and the technology adequate to it can be used in the operation of any rotary and (or) piston type equipment. It is important to keep in mind that formed according to similar characteristics (see Fig. 6) harbingers of development of emergency situations at NTOs are systemic. They are suitable for solving problems of identifying the type of developing accident — local and systemic (disaster).

Figures 7 and 8 present experimentally reproducible systemic patterns of interaction between gas pumping units (GPU). They were worked out at the Orlovka-2 gas pumping station (Ukraine) and are not fundamentally monitored by ALARP-based systems. The total number of field tests according to Fig. 7 (GPU-1 → GPU-2) is 14, according to Fig. 8 ("GPU—4 → GPU-5") is 18.

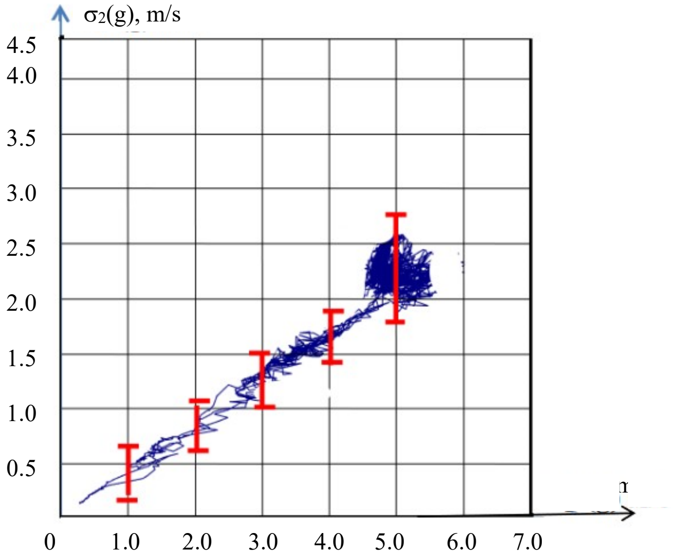

Fig. 7. GPS "Orlovka-2" (Ukraine). Reproducible patterns of interaction "GPU-1 → GPU-2"

Technosphere Safety

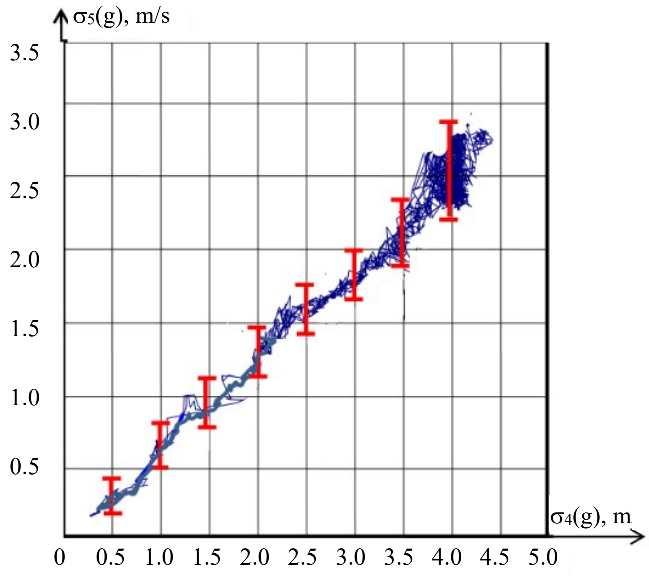

Fig. 8. GPS "Orlovka-2" (Ukraine). Reproducible patterns of system interaction "GPU-4 → GPU-7"

In the figures, the patterns are shown in the form of hodographs in the form of dependencies, measured in the horizontal and vertical directions of the mean square root values of the vibration velocities of the GPU on the total gas flow through the GPS — *g*. For certainty, the frequency range of measurements of mean square root values of 0.1–5 Hz was chosen. According to statistics, it is in this range that processes with a large self-organized concentration of energy often occur in NTO structures, which provoke the development of emergency outcomes — both local and more costly systemic ones. Despite the significant differences in the physical mechanisms, in this case, the results obtained can be used in the operation of rotary-type equipment, and with appropriate adaptation in the operation of non-rotary equipment.

For the development of the above-mentioned prototype of the DRS and the Strategy of the Russian Federation for countering the development of systemic accidents [1, 3], are essential:

– reproducibility of the results of field tests;

– experimental validity of statistically correct applied results.

Let us also note the importance of the typical scenario expected by specialists for the development of systemic accidents of different physical nature. It took at least ten years of targeted scientific and experimental work to confirm the reproducibility of the results. This made it possible to implement in the DRS and then reflect in the Strategy of the Russian Federation a set of unified algorithms and technical means for early detection, monitoring and protection against all types of man-made accidents.

An extremely important quality of this complex has been worked out — object orientability (the possibility of deep adaptation to almost any standard sizes of the NTO infrastructure).

We also note a characteristic feature of the system approach, which allows us to draw the right conclusions even if the experimental reproducibility of the results of the NTO full-scale tests is weak or not detected at all. It should be borne in mind that the same element of a complex system (for example, a compressor) demonstrates different properties and behavior, even if it functions as part of a single NTO. It depends on whether the situation is considered before or after the repair. This effect is easily confused with poor reproducibility of compressor test results.

Comparative analysis results of emergency protection systems adequate to the ALARP principle and the CSTP system approach. In almost all publications related to the ALARP principle, there are conditions from which ALARP proceeds. For some reason, they have to be executed by themselves, and this is a reason for criticism. The ALARP principle can be unconditionally used for a class of objects that are collections of such objects that are not related to each other, do not interact and are statistically independent. Thus, the usefulness of ALARP is limited to individual studies outside the system of each element of the NTO. Also, outside the system, the class of local accidents inherent in the elements is considered. The ALARP principle is not suitable for an adequate study of NTO as a whole structure, the formation of adequate symptoms, decision-making algorithms, etc. Using any tools based on the ALARP ideology (and EPS as well), we must understand that we are going to a conscious restriction.

The only way out seems to be the rapid creation of safety systems that are alternative to those that focus on ALARP. The foundation for new solutions should be the foundation formed for the implementation of a comprehensive scientific and technical program "Creation of innovative software and hardware and technologies to ensure the observability, manageability and safety of natural and man-made infrastructure facilities in Russia".

Here are the main arguments for the readiness to create safety and emergency protection systems within the framework of the CSTP as an alternative to the EPS according to the ideology of ALARP.

– Certified prototypes of professional tools have been created, including in explosion-proof design, for experimental testing of components of the system for countering the development of accidents and catastrophes.

– Emergency protection systems according to the CSTP are based on combined local and systemic approaches to the study of the NTO infrastructure within the framework of the theory of self-organized criticality [3].

– The emergency protection systems according to the CSTP take into account the discovery of the 50–60s of the Russian space engine industry [6]. We are talking about two types of the physical nature of accidents. In modern terminology, they are called local (in the NTO elements) and large-scale, systemic (in NTO as an integral functional unit). According to the ALARP scheme, the EPS reacts to the development of only low-cost local accidents.

– Emergency protection systems according to the CSTP are ready to make motivated decisions about the beginning of the development of all types of local accidents and systemic accidents in the NTO. This distinguishes them from EPS according to the ALARP scheme, which reacts only to local accidents.

– In the emergency protection systems according to the CSTP, the readiness to transfer the NTO to a safe state has been achieved in two scenarios. The first one is the transfer of the NTO to gentle modes of operation. Second: emergency shutdown in response to motivated decisions about the development of emergency critical situations.

– Restrictions on the scope of application of emergency protection systems according to the CSTP according to the type of a priori conditions for EPS according to the ALARP scheme have been lifted.

– In emergency protection systems according to the CSTP, the symptoms of the development of local, systemic critical conditions of NTO and the rules for making decisions on the transfer of NTO to a safe state have been scientifically and experimentally worked out.

– Readiness has been achieved (when making an appropriate decision) to work out a high-speed mechanism for transferring the NTO to a safe state for the most dangerous explosive-type accidents with a characteristic development time $\Delta t \approx 30–70$ ms.

Discussion and Conclusion. The emergency protection systems developed according to the CSTP "Observability, manageability, safety of the NTO infrastructure of Russia" are considered. Their capabilities are evaluated in the conditions of the Northwestern region of the Russian Federation [1]. The new approach is compared with the ALARP principle, which is widespread in the West and in Russia.

It is shown that ALARP has outlived its usefulness, since its local orientation does not meet the tasks of system monitoring of the IT infrastructure [8–14]. The ALARP approach remained at the level adopted at least 100 years ago, in the first half of the twentieth century. This is how it is necessary to evaluate developments implemented under the ALARP scheme and their output products, including emergency protection systems [8–14].

Research and practice indicate that the ALARP methodology does not provide comprehensive observability, manageability, and safety of natural and man-made infrastructure facilities. For this reason, the ALARP-based approach does not provide timely, high-quality indication of the development of devastating system crashes — catastrophes.

Emergency protection systems created according to the proposed CSTP project integrate local and integrated approaches to infrastructure monitoring within the framework of the theory of self-organized criticality [3].

The prospects of replacing ALARP-based approaches with solutions corresponding to the CSTP are shown.

References

1. Deduchenko FM. Tekhnologicheskie, ekologicheskie i organizatsionnye aspekty obespecheniya prirodno-tekhnogennoi bezopasnosti neftegazovoi otrasli Rossii. In: *Puti realizatsii neftegazovogo potentsiala Zapadnoi Sibiri. Mat-ly XXV nauch.-prakt. konf.* Khanty-Mansiysk: V.I.Shpilman research and analytical centre for the rational use of the subsoil; 2022. P. 12–28. (In Russ.).

2. Dmitrievskii AN, Mastepanov AM, Bushuev VV. Resource-innovative strategy of Russia's economic development. *Herald of the Russian Academy of Sciences.* 2014;84(10):867–873. https://doi.org/10.7868/S0869587314100077 (In Russ.).

3. Bak P. *Kak rabotaet priroda. Teoriya samoorganizovannoi kritichnosti.* Moscow: URSS; 2022. 288 p. (In Russ.).

4. Malinetskii GG. Chudo samoorganizovannoi kritichnosti. In book: *Kak rabotaet priroda. Teoriya samoorganizovannoi kritichnosti.* Moscow: URSS; 2022. P. 13–44. (In Russ.).

5. Akimov VA, Deduchenko FM, Durnev RA, Rvachev AT, Arabskii AK, Kulchitskii AB, et al. Kontseptsiya sozdaniya edinoi sistemy kompleksnoi tekhnogennoi bezopasnosti i zashchishchennosti promyslov neftegazovogo kompleksa RF. *Gazovaya promyshlennost'.* 2015;(S4(732));70–83

6. Deduchenko FM. Project of counteracting catastrophic developments at nature-man-made objects in Russia. *Safety and Reliability of Power Industry.* 2021;14(3):111–117. https://doi.org/10.24223/1999-5555-2021-14-3-111-117 (In Russ.).

7. Cox LA. What's wrong with risk matrices? *Risk analysis*. 2008;28(2):497–511. https://doi.org/10.1111/j.1539-6924.2008.01030.x

8. Pickering A, Cowley SP. Risk matrices: implied accuracy and false assumptions. *Journal of Health & Safety Research & Practice*. 2010;2(1):11–18. URL: https://edisciplinas.usp.br/pluginfile.php/7634511/-mod_resource/content/0/Risk%20matrices%20false%20assumptions.pdf (accessed: 02.10.2023)

9. Bychkov S, Rudnitska R, Maggs R, Kesteren M, Aramyan G, Németh E, et al. *Risk assessment in audit planning. A guide for auditors on how best to assess risks when planning audit work.* 2014. 46 p. URL: https://www.pempal.org/sites/pempal/files/event/attachments/cross_day-2_4_pempal-iacop-risk-assessment-in-audit-planning_eng.pdf.

10. Novozhilov EO. Guidelines for construction of a risk matrix. *Dependability*. 2015;3:73–86. https://doi.org/10.21683/1729-2646-2015-0-3-73-86 (In Russ.).

11. Karmanov AV, Telyuk AS, Shershukova KP. ALARP principal implementation while performing synthesis of milti-channel emergency protection system. *Avtomatizatsiya, telemekhanizatsiya i svyaz' v neftyanoi promyshlennosti.* 2014;6:36–40. (In Russ.).

12. Telyuk AS. *Sintez sistem protivoavariinoi zashchity dlya protsessov podgotovki produktsii neftegazovykh skvazhin.* Author's thesis. Moscow; 2014. 24 p. URL: https://new-disser.ru/_avtoreferats/01007881385.pdf?ysclid=lpmoogd1bk891406616 (accessed: 02.10.2023) (In Russ.).

13. Telyuk AS. Programmnoe obespechenie avtomatizirovannogo sinteza sistem protivoavariinykh zashchit. *Avtomatizatsiya, telemekhanizatsiya i svyaz' v neftyanoi promyshlennosti*. 2014;1:36–39. (In Russ.).

14. Gapanovich VA, Shubinsky IB, Zamyshlyaev AM. Risk assessment of a system with diverse elements. *Dependability*. 2016;2:49–53. 2016;(2):49–53. https://doi.org/10.21683/1729-2640-2016-16-2-49-53 (In Russ.).

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AN Dmitrievsky: academic advising, analysis of the research results, revision of the text, correction of the conclusions.

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