ГОРНОПРОМЫШЛЕННАЯ И НЕФТЕГАЗОВАЯ ГЕОЛОГИЯ, ГЕОФИЗИКА

DOI: 10.21440/0536-1028-2021-8-24-33

Ensuring industrial safety when drilling wells and developing oil and gas field infrastructure on the shelf of the Arctic and Subarctic seas

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Abstract
Introduction. *The Arctic and the Far East shelf has a true and considerable potential for existing and new oil and gas fields development in the Barents, Kara, and Okhotsk seas. Projects on the continental shelf are closely connected to Russia's integrated development and quality of life, therefore being of prime national importance. The paper considers natural and man-induced hazards found in the course of exploration drilling and offshore field infrastructure development in freezing seas and high crustal seismicity. Risk management and industrial safety technologies are described in the paper.*
Research objective *is to obtain reliable information on the state of the environment and mineral resourses on the continental shelf of Arctic and Subarctic seas to ensure the safety of offshore oil and gas field development.*
Methods of research *included the complex analysis of natural hazards of the Russian shelf, including shallow methane, gas hydrates, ice load, and man-induced hazards, namely offshore blowouts, gas lenses penetration when drilling, and permafrost thawing. The data from geological engineering survey, marine electrical prospecting, geophysical well logging, drilling and the history of offshore field development have been studied.*
Research results. *A problem of safe offshore operations has been revealed. The problem may be efficiently solved by using advanced technologies for natural and man-induced hazard identification and prevention. Shallow gas deposited in the upper part of the section has been discovered for the first time through the results of geophysical well logging at the fields of the Gulfs of Ob and Taz.*
Conclusions. *Safe offshore production requires the comprehensive study of the project area's natural and climatic conditions, as well as geological engineering survey, marine work data analysis, and deep hole surveys. It will make it possible to identify hazardous natural geological processes and prevent man-induced impact on the delicate environment when developing shelf oil and gas resources.*

Keywords: *shelf; drilling; offshore fields; field infrastructure development; man-induced hazard; natural hazard; oil and gas resources; gas hydrates; shallow gas; permafrost.*

Introduction. Apart from rich oil and gas fields development, Arctic policy includes the development of new industrial regions, Northern Sea Route and coastal infrastructure for an intercontinental water route, cross-polar flights, indigenous peoples' protection, and environmental safety.

Projects on the continental shelf are closely connected to Russia's integrated development, therefore being of prime national importance. Hydrocarbon production affects national security, energy industry, and transport directly.

The development of Arctic shelf resources requires environmental obligations fulfillment. Large-scale technical solutions on the shelf should be based on a scientifically grounded concept of a single natural-economic complex [1].

Research objective is to obtain reliable information on the state of the environment and mineral resourses on the continental shelf of Arctic and Subarctic seas to ensure the safety of offshore fields development.

Analysis and discussion. The initial total in-place hydrocarbon resources of the Russian Arctic are estimated at about 120.9 billion toe (ton of oil equivalent), i.e. 100.4 billion toe of free gas, 16.6 billion toe of oil, 2.9 billion toe of condensate, and 1.1 billion toe of dissolved gas, which is about 27% of Russia's hydrocarbon resources [2, 3]. Besides, the unexplored potential of the Arctic shelf is more than 90%.

The projects of Prirazlomnoye field development in the Pechora Sea and Sakhalin-1, Sakhalin-2, Sakhalin-3 in the Sea of Okhotsk on the Sakhalin island shelf have currently been implemented on the shelf of Russia's freezing seas.

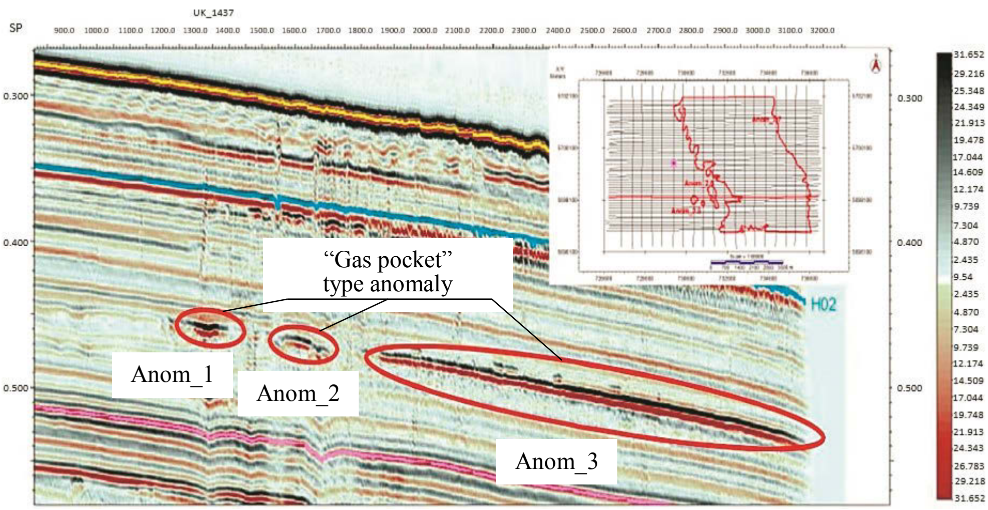

Figure 1. Gas lenses in the upper part of geological section of the Sakhalin shelf
Рисунок 1. Газовые линзы в верхней части разреза шельфа о. Сахалин

The safety and reliability of offshore structures depend on a wide range of natural and man-induced factors. Natural hazards carrying certain risks for hydrocarbon field development, especially for offshore well drilling, are as follows: shallow deposits with an increased gas saturation (gas lenses) characterized by abnormal high pressure (AHP), and accumulations of gas hydrates, permafrost, and ice impact on oil and gas facilities and seabed.

Each section of the shelf is often specified by an individual set of hazards, depending on the geomorphological or geographical position [4].

Shallow gas. Gas-saturated sediments in the bottom part of the sedimentary cover are quite common. The data of long-term geophysical and geological engineering surveys in various regions of the Arctic confirm this fact [5]. They are found at a depth of 10–40 m from the seafloor being quite local with a small lateral extent. Larger gas objects are found at depths from 100 to 800 m (Figure 1).

When such accumulations are penetrated, downhole fluid emission complicates drilling and might cause an emergency, since the drilling rig might lose buoyancy due to the reduced density of seawater and scoured footing of a jack-up rig or gravity based platforms. Upon reaching a critical concentration in the air, gas fluid might cause an explosion of a gas-air cloud. Permafrost can create conditions for gas concentration with APH intervals development. In this respect, the intervals found on the permafrost floor are the most dangerous.

Gas-saturated zones also affect the choice of exploration or wild-cat drilling platforms location and field infrastructure facilities. The hazard is serious due to gas in the soil that reduces its strength. Neglect of this factor or soil mechanical properties miscalculation might result in critical displacements of platforms, subsea manifolds substructures, compressor stations and other facilities because of the low bearing capacity of bottom sediments. Gravitational processes become more intense, soils get floating properties, their tendency to liquefaction increases, chemical aggressiveness and the ability to corrode metal grow.

Integrated interpretation of the geophysical well logging (GWL) data from gas condensate fields of Kara's Sea Gulfs of Ob and Taz was carried out to discover shallow gas. Shallow gas deposited in the form of separate beds has been discovered for the first time based on the GWL data at the fields of Chugoriakhinskoye, Ob and Semakovskoye through the anomalies of rocks apparent resistivity: at depths of 228 and 283 m with a thickness of 1 and 1.5 m (in the Chugoriakhinskoye well no. 2), at depths 408 and 448 m with a thickness of 2 and 1 m, respectively (in the Ob well no. 1) and at a depth of 766 m (in the Semakovskoye well no. 101) (Figure 2).

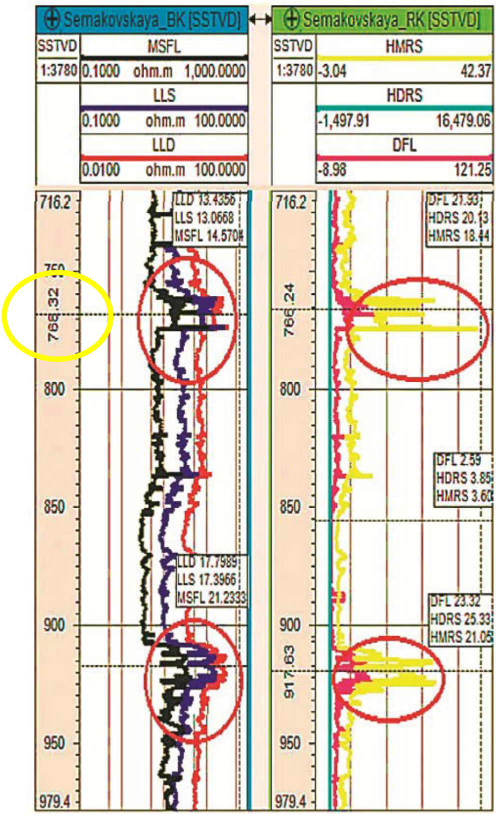

Figure 2. An example of shallow gas identification at a depth of 766 m according the well logging (LLS, LLD and DFL, HDRM, HMRS) interpretation of the Semakovsky well no. 101. The top of the productive gas reservoir is located at a depth of 908 m

Рисунок 2. Пример выделения линзы приповерхностного газа на глубине 766 м по результатам ГИС методом БК (LLS, LLD) и ИК (DFL, HDRM, HMRS) скважины Семаковская № 101. На глубине 908 м расположена кровля продуктивного газового пласта

The presence of gas in the section is out of the question. One of the reasons for these shallow gas may be sub-vertical migration from the Cenomanian. Pilot holes are drilled to minimize the risk making it possible to confirm shallow gas presence or absence.

Gas hydrates. In nature, gas hydrates embedded close to the surface exist in conditions close to their phase-stability boundary being extremely sensitive to temperature, and man-induced baric and chemical impacts. Besides, natural warming in the Arctic of the last 10–20 years reduces relict gas hydrates "overcooling" therefore increasing gas hazard. Above listed factors are among the main sources of man-induced problems of field development in the northern latitudes. Gas hydrates can decompose for years and decades as a heatwave moves from a facility (for example, from a development wellbore) or as the climate warms from the surface deep into the frozen massif [6].

Relict gas hydrates decomposition and, as a rule, intense gas ingress result from the man-induced impact of hydrate saturated rocks on the rock mass, especially when drilling and operating wells. In this case, large amounts of fresh hydrated moisture are released in the saline section, which results in rock thermophysical properties and phase equilibrium change [7, 8].

Permafrost. Permafrost study is of great practical importance both from an engineering-geological point of view (drilling of offshore exploration and production wells) and in terms of oil and gas content study when carrying out regional geological and geophysical work.

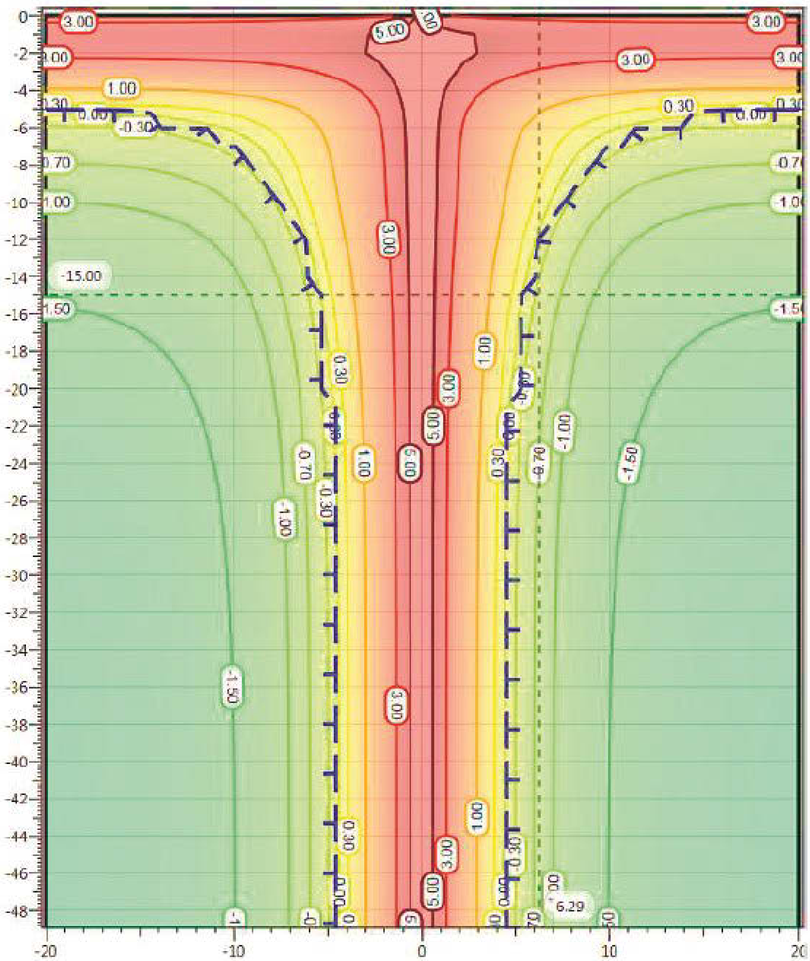

Figure 3. Fragment of the temperature field formed in the 30th year of operation of a gas production well with a gas temperature of +15 °C for a sandy-loamy section
Рисунок 3. Фрагмент температурного поля, сформированного на 30-й год эксплуатации газодобывающей скважины с температурой газа +15 °С для песчано-суглинистого разреза

The existing experience amply reveals serious problems of design, construction and operation of offshore engineering structures on permafrost. Thaw aureole constitutes the main danger for offshore engineering structures. The ground thaws due to the long-term thermal impact of wells on icy permafrost. Thawing causes uneven soil subsidence, thermokarst sinkholes, as a result, damage offshore engineering structures.

Even if the conductor strings are thermally insulated, permafrost thaws in the course of gas production well operation due to the high temperature of the produced gas. By the example of the Semakovskoye field, thaw aureole development dynamics is shown in Figure 3 (zero amplitude temperature is –2.3 °C [9]). The look-ahead

Table 1. Ice situation in the seas of the Arctic and the Russian Far East
Таблица 1. Ледовая обстановка в морях Арктики и Дальнего Востока России

Sea area	The presence of the permafrost/icebergs	Mean maximum thickness of the level ice floe, m	Integrated duration of a level ice floe of various thicknesses, weeks					
			Open water or ice less than 10%	Conventional thickness of the level ice floe (ignoring greater thickness of ice under gouging)				
				Less than 0.3 m	Less than 0.6 m	Less than 1 m	Less than 1.4 m	1,4 m and more
Barents Sea, south (Pechora)	No	0.9	13	10	4	10	10	5
Barents Sea, northeast	Present, frequent	1.5	13	4	6	10	9	10
Kara Sea, southwest	No /rare	1.2	9	10	6	6	6	15
Kara Sea, northeast	Present, frequent	1.8	3	6	5	3	2	33
Laptev Sea	Present	2.0	10	3	6	7	5	21
East Siberian Sea	Present	2.3	9	4	5	6	8	20
Chukchi Sea	Rare	1.8	12	3	5	6	8	18
Bering Sea	No	1.2	30	3	5	12	2	0
Sea of Okhotsk	No	1.2	26	4	6	14	2	0
Sea of Japan, north	No	0.4	40	8	4	0	0	0

thermotechnical calculations of the 30 years' operation of a well with a heat-insulated structure in permafrost revealed that permafrost thaw aureole radius around the well reaches 13 m under a gas temperature of +60 ° C.

Complementary technical solutions for soil temperature stabilization will make it possible to create the necessary thermal regime, reduce the warming effect, and exclude hazardous geological and geocryological processes [9].

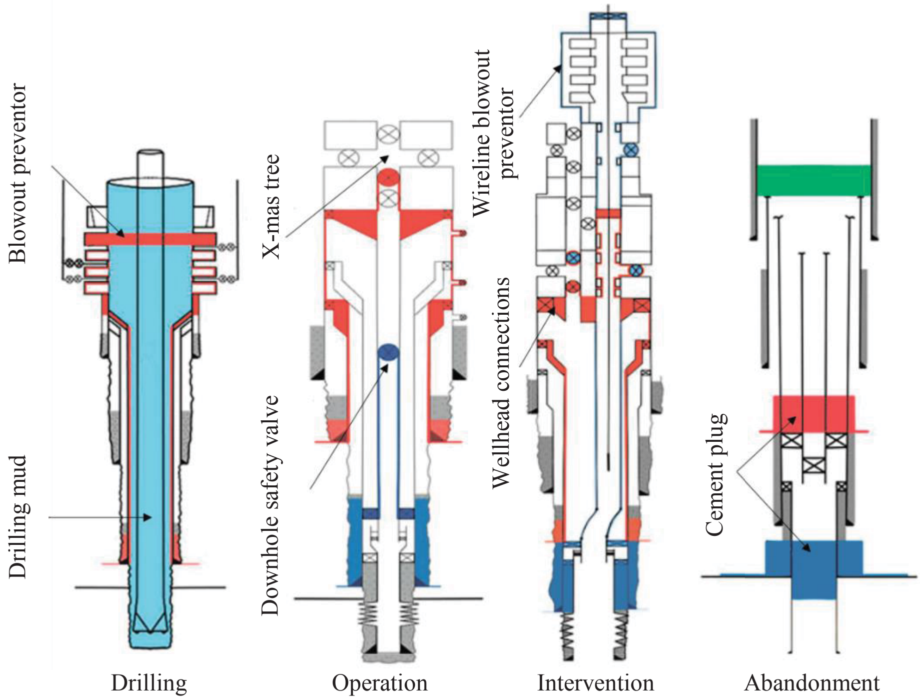

Figure 4. Illustration of the two-barrier philosophy throughout a well's lifecycle
Рисунок 4. Иллюстрация двухбарьерного принципа на протяжении всего жизненного цикла скважины

Permafrost thawing might create complications causing the degradation of well lateral support in a certain depth interval and, as a result, longitudinal stability loss under the action of vertical loads. Under gas hydrate saturation of the permafrost, ice formation in the casing string annulus is another complication apart from the annual gas ingress in the near-wellbore zone. It might result in the development of increased pressures impacting the well support. Manifestation of abnormal pressures arising from aqueous bodies freezing in the casing string annulus causes hydraulic fracturing of the surrounding frozen rock, production, surface and other strings buckling, the surface and conductor string failure under the refreezing pressure which exceeds the critical internal yield pressure.

The merger of the thaw zones developed at well pad design causes the hazard of well support destabilization due to cluster pad base rigidity violation and substantial increase in negative friction forces.

Ice impact. On average, the inter-ice period of the Russian Arctic continental shelf is 2–2.5 months. In some Arctic regions, ice is sometimes present all year round [10] (Table 1).

The thickness of first-year sea ice can reach 1.3–1.5 m and more. Multi-year ice can be thicker. Concentrating near the coast due to currents and wind, ice forms ice floes, hummocks, stamukhas, and piles, which produce ice gouging on the seafloor, which can violate the integrity of the subsea structures.

Ice gouging also causes the development of seafloor gouges with sufficient slope angles, which might harm the stability of structures. At shallow depths (the first tens of meters), sediments fill the gouges due to lithodynamic processes, which can be one of the reasons for the heterogeneous structure of the upper part that is several meters thick. It is a complicating factor, for example, in setting jack-up rigs.

From all that has been said, it is obvious that a high level of ice protection should be provided at all offshore oil and gas field facilities in the freezing seas [11–13].

Prevention of offshore subsea blowouts. Offshore wells construction and operation are associated with the risk of oil, gas and water showing that can turn into blowouts in case safety barriers are violated. Figure 4 shows the safety barriers preventing the uncontrolled release of downhole fluid at different stages of well life cycle (drilling, operation, intervention and abandonment) [14].

Fields are developed for 30–35 years. The integrity of wells and subsea equipment may be destroyed as a result of long-term operation, natural wear and tear, and seismic events typical of some regions, causing blowouts.

Blowout as an uncontrolled release of downhole fluid (oil, gas or water) from a well into the environment can cause human deaths and irreparable environmental damage, despite the low likelihood of occurrence. Gulf of Mexico disaster that shocked the oil and gas industry in 2010 was a serious notice for offshore companies to be prepared to respond to such emergencies.

Relief well construction and dynamic kill injection into the blowing well is a way of subsea blowouts response.

Another way of blowouts response is the method of directing subsea capping stack at the emergency wellhead with its further sealing. This method involves several specialized vessels in emergency operations. The performance depends on the flowrate of the blowing well, sea depth, direction of currents, etc. [15].

Conclusions. A problem of safe operations on the shelf has been revealed based on the data from the geological-engineering survey, marine electrical exploration, geophysical well logging, drilling and the history of offshore field development. The problem can be successfully solved by using modern technologies for identifying and preventing natural and man-induced hazards.

Safe offshore production requires the comprehensive study of the project area's natural and climatic conditions, as well as geological engineering survey, marine work data analysis, and deep hole surveys. It will make it possible to identify hazardous natural geological processes and prevent man-induced impact on the delicate environment when developing shelf oil and gas resources.

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Received 2 November 2021

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УДК 551.2.05 DOI: 10.21440/0536-1028-2021-8-24-33

Проблемы промышленной безопасности при бурении скважин и обустройстве нефтегазовых месторождений на шельфе арктических и субарктических морей

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Реферат
Введение. *Шельф арктических морей и Дальнего Востока обладает реальным и значительным резервом для выявления новых нефтегазовых месторождений и освоения ранее открытых в Баренцевом, Карском и Охотском морях. Проекты на континентальном шельфе имеют особую значимость для России, поскольку они напрямую связаны с комплексным развитием страны и повышением качества жизни населения. В статье рассмотрены природные и техногенные опасности, выявленные при поисково-разведочном бурении скважин и обустройстве морских месторождений в условиях замерзающих морей и высокой сейсмичности земной коры. Описываются технологии выявления и предупреждения возникающих рисков и технические решения, обеспечивающие промышленную безопасность.*
Целью исследования *является получение достоверной информации о состоянии окружающей среды и недр на континентальном шельфе арктических и субарктических морей для обеспечения безопасного ведения работ при освоении морских нефтегазовых месторождений.*

Методика проведения исследований *заключалась в комплексном анализе существующих на российском шельфе природных опасностей: мелкозалегающий метановый газ, газогидраты, ледовые нагрузки; а также техногенных опасностей: открытое фонтанирование морских скважин, вскрытие газовых линз при бурении скважин и растепление многолетнемерзлых пород. Исследованы результаты инженерно-геологических изысканий, данные морской электроразведки, геофизических исследований скважин, бурения и истории разработки морских месторождений.*
Результаты. *Показано, что существует проблема безопасного ведения работ на шельфе, которая может быть успешно решена путем применения современных технологий выявления и предупреждения природных и техногенных опасностей. Впервые по результатам геофизических исследований скважин на месторождениях Обской и Тазовской губ выявлено наличие мелкозалегающего газа в верхней части разреза.*
Выводы. *Сделан вывод о том, что для безопасного освоения морских нефтегазовых месторождений следует проводить комплексное изучение природно-климатических условий района работ, инженерно-геологические изыскания, анализ данных морских геофизических работ и исследований глубоких скважин. Это позволит выявлять опасные природные геологические процессы и обеспечивать предупреждение техногенного воздействия на хрупкую природную среду при освоении нефтегазовых ресурсов шельфа морей.*

Ключевые слова: *шельф; бурение; морские месторождения; обустройство месторождения; техногенная опасность; природная опасность; нефтегазовые ресурсы; газовые гидраты; мелкозалегающий газ; многолетнемерзлые породы.*

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Поступила в редакцию 2 ноября 2021 года

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Для цитирования: Дзюбло А. Д., Перекрестов В. Е., Алексеева К. В. Проблемы промышленной безопасности при бурении скважин и обустройстве нефтегазовых месторождений на шельфе арктических и субарктических морей // Известия вузов. Горный журнал. 2021. № 8. С. 24–33 (In Eng.). DOI: 10.21440/0536-1028-2021-8-24-33
For citation: Dziublo A. D., Perekrestov V. E., Alekseeva K. V. Ensuring industrial safety when drilling wells and developing oil and gas field infrastructure on the shelf of the Arctic and Subarctic seas. *Izvestiya vysshikh uchebnykh zavedenii. Gornyi zhurnal = Minerals and Mining Engineering*. 2021; 8: 24–33. DOI: 10.21440/0536-1028-2021-8-24-33