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Conceptual project of a center for testing technologies and technical devices for glacier drilling

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Abstract. The implementation of drilling projects in Antarctica requires comprehensive research and development work to study the processes of interaction between drilling equipment and ice and test devices designed for ice drilling. Testing facilities with artificial ice are essential for conducting this type of research. The article presents an analysis of the existing experimental stand projects, which identified a common drawback — inability to recreate a structure of atmospheric ice and thermobaric conditions similar to those in boreholes drilled in Antarctica. The authors propose the conceptual project of a center for testing technologies and technical devices for glacier drilling. The center is to be located on two sites: the first — on the "Sablino" educational and scientific testing ground of Saint-Petersburg Mining University in the Leningrad Region (Russia), the second — at the drilling complex of 5G borehole at Vostok station in Antarctica. The implementation of the project will allow conducting experimental research and testing, using both shallow artificial ice wells and deep boreholes in the Antarctic glacier. In addition, it will allow maintaining the drilling complex and 5G borehole in a good technical condition.

Keywords: Antarctica, artificial ice borehole, borehole 5G, drilling process, drilling technologies and equipment, testing center

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1. Introduction

Since the mid-20th century, the world's leading countries, including the Russian Federation, have been engaged in active research in Antarctica. Many of the research projects involve drilling into glaciers to collect ice cores or access subglacial water bodies and rocks for geological, paleoclimatic, and biological studies [1]. In the former case, scientists obtain ice core material, which is a unique source of information about the climatic processes that have occurred on the sixth continent over the past few million years [2, 3]. In the latter case, scientists get quick access to subglacial reservoirs and bedrock to conduct geological, paleo-climatic and biological research [4–6].

St. Petersburg Mining University, in collaboration with the Arctic and Antarctic Research Institute (AARI), has been conducting scientific research at Vostok Station for over five decades. This work involves drilling deep boreholes into glaciers and studying the resulting cores. In this time, technologies and technical devices have been developed and applied, which made it possible to set several world records in glacier drilling [7, 8] and to unseal subglacial Lake Vostok twice [9, 10].

The testing of the technologies and equipment developed was often carried out directly during the process of deep ice drilling, which led to increased risks of emergency situations and prolonged project duration. The mechanical and thermal destruction of ice differs significantly from the processes occurring during the destruction of rocks [11, 12]. This necessitates the adaptation of the existing drilling technologies and the development of new ones, taking into account the mining, geological, and physic-geographical conditions of the Antarctic [13]. These activities require comprehensive research and development, including experimental studies on the interaction of drilling tools with ice and the testing of the technical devices developed [14, 15].

A solution to these problems can be worked out on experimental stands that use various methods for modeling ice masses:

– using single ice blocks (artificial or natural);
– using ice towers;
– using ice wells.

Each of the methods listed has its own advantages and disadvantages, which are discussed below.

Projects using single ice blocks

In the early 1980s, an experimental setup was developed at Leningrad Mining Institute (now St. Petersburg Mining University) to simulate the operating conditions of an ice core electromechanical drill (KEMS) attached to a carrying cable using single ice blocks [16]. The experimental stand was used at Vostok station. This enabled research on the drilling equipment of the 5G borehole complex with the circulation of the drilling fluids used. The main disadvantage of the setup was the artificial model of the bottom hole with limited dimensions, which did not allow for the required run length, as well as the difference in the physical and mechanical properties between the ice block and the glacier.

In 1988, a team of Japanese researchers conducted a study on ice cutting, collection and transportation and tested the electronics used in the drilling equipment (Tachikawa, Tokyo, Japan) [17]. The research was conducted on a 20 m tall derrick with a refrigeration chamber at the base, which provided circulation of cooled kerosene and housed an ice block measuring 0.2 × 0.6 × 0.9 m. The chamber had a window for observing the drilling process. The main disadvantages of the experimental setup include: the cooling system did not allow the temperature of the ice and kerosene to be lower than –5 °C; the dimensions of the ice block limit the number of tests (to three).

In 1994, a group of Japanese scientists developed a more advanced experimental stand for studying the ice cutting process [18], with pressure ranging from 0.1 to 30 MPa at temperatures of up to –62 °C. The stand’s disadvantage was that its working chamber was too small to accommodate a drill.

In 2015, Chinese scientists conducted research to determine the relationships between the geometric parameters of ice cuttings and the drilling parameters of an electromechanical auger drill [19]. A special experimental setup was made, including a mechanical part and an ice block measuring 0.7×0.6×0.5 m, prepared from lake ice at a temperature of no more than –5 °C. The mechanical part of the setup contained a 2 m high mast with a drill suspended on it. The drill was equipped with a single-cutter bit. The parameters of the drilling modes and the temperature of the ice were recorded by sensors. The main disadvantages of the experimental stand include the lack of an anti-torque system, which causes significant vibration during projectile operation and distortion of the results obtained; and the characteristics of the lake ice not corresponding to those of the atmospheric ice in Antarctica.

Projects using ice towers

The arrangement of ice blocks in the form of towers provides an increased depth for experimental drilling and testing of full-scale drilling equipment.

The first experimental complex for studying the ice drilling process was built during the times of the Russian Empire at the Tomsk Technological Institute in the winter of 1909 [20].The author of the project was Boris Petrovich Weinberg, a famous Russian physicist and glaciologist, who proposed the theory of ice movement along an inclined channel, and studied the movement of Arctic ice and its physical and mechanical properties. The complex consisted of a tower 10 m high, where ice was frozen naturally by gradually moving a box of steel sheets and adding water. This complex was used to test the first thermal drill designed for drilling boreholes in ice.

One of the most significant international ice tower projects was the research conducted by Japanese scientists between 1992 and 1993. This research aimed to test drilling systems with fluid in polar conditions. In Rikubetsu city, which is located in the coldest region of Japan, a 30-meter-high testing facility was built, with a 15-meter-tall ice tower made of 1 × 1 m ice blocks. Before beginning the experiments, pilot holes with a depth of 8 m were drilled in the ice tower and filled with drilling fluid to a height of 7 m. The tower's cross-sectional area was sufficient to drill nine holes, with a total drilling depth of 63 m. However, despite the low air temperatures in winter (down to –25 °C), the experimental conditions were insufficiently similar to those in which drilling was carried out in Dome F, Antarctica.

An example of modern experimental research experience using an ice tower is the testing of the RECAS (RECoverable Autonomous Sonde) thermal probe [Pavel Talalay, personal communication]. In the winter of 2021, a 15 m high tower made of lake ice blocks was constructed on Hongqi Lake in Changchun, China. The lake's depth of 3 m made it possible to conduct successful experiments on collecting water samples from a reservoir using a probe. However, during the equipment testing, meltwater leaked between the ice blocks, leading to overheating of the probe's elements.

Ice wells projects

Another glacier modeling method is to use ice wells. This method was first used in 1964 in Hanover (USA) to test drilling tools developed by the Cold Regions Research and Engineering Laboratory (CRELL). The ice was formed in a special structure with a diameter of 1.22 m and a depth of 63 m. The structure consisted of pipe sections and an internal coolant circulation system. However, during the research, the well was depressurized, and the drilling fluid polluted the environment [21].

Another example of an artificial ice well where equipment was tested is the Laboratory of Glaciology and Geophysics of Environment in Grenoble (France). To test drilling technologies, researchers created an 8 m deep pit, in which ice was frozen. The shallow depth of this structure made it impossible to test a full-size drill, so the final stages of equipment testing were carried out in Antarctica [22].

A distinctive feature of the ice well created in 2015 at the University of Minnesota (USA) was the principle of ice freezing due to the circulation of a coolant in the annular channel between the casing and a pipe simulating a well. The working depth of the well was 152 m with a diameter of 124.2 mm. Liquid coolant CO_2 circulated through the annular space of the well, providing an ice temperature in the range from –25 to –40°C. However, the small diameter of the well caused frequent contact between the drilling tool and the wall of the pipe, resulting in damage. During the tests, difficulties were observed in supplying the coolant to the annular space, leading to difficulties in the process of ice freezing. A lack of refrigerant flow in the well prevented its use as a permanent testing facility. After the completion of the testing program for a mechanical drilling rig, the facility was decommissioned [23].

One of the significant projects currently using ice wells is the ice drilling test facility at the Polar Research Center of Jilin University in China [21]. In this project, artificial ice is frozen in a pipe with an internal diameter of 1 m and a wall thickness of 10 mm, which is installed in a shaft at a depth of 12.5 m. The shaft has a diameter of 2.6 m and is covered by a waterproof casing. The annular space between the ice well and the walls of the shaft contains evaporator coils and thermal insulation, which also serves as a space for equipment maintenance and repairs. The ice well can be used to test technical devices for glacier drilling and its main advantages include:

– the ability to simulate various environments and geological conditions;

– the ability to regulate the temperature of ice over a wide range;

– high technological efficiency of the design allowing one to perform a series of tests under identical conditions.

Some disadvantages of this structure include the complexity of installation works, high requirements for the quality of the underground part, and the complexity of maintaining cryogenic equipment [24]. Of all the methods of glacier modeling, the most universal is the creation of artificial ice wells. These models are part of testing facilities that allow year-round testing of drilling techniques and equipment. However, like other methods, this method of modeling ice mass cannot recreate the structure of atmospheric ice or the thermobaric conditions at boreholes in Antarctica, which directly affects the design features of drilling tools and the drilling process.

2. Glacier drilling technology and equipment testing center

The Center for testing technologies and technical devices for glacier drilling is to be located on two sites:

1) on the "Sablino" educational and scientific testing ground of Empress Catherine II Saint-Petersburg Mining University in the Leningrad region (Russia);

2) at the drilling complex at Vostok station in Antarctica, where a 5G deep borehole has been drilled.

At the first site, drilling equipment will be tested in an artificial ice well. At the second location, the tests will be conducted in conditions of a deep borehole in the glacier.

The possibility of constructing a complex with two ice wells, similar to the design of the Jilin University Polar Research Center, is being investigated on the "Sablino" testing ground. The complex will be housed in a building measuring 18 m long, 15 m width, and

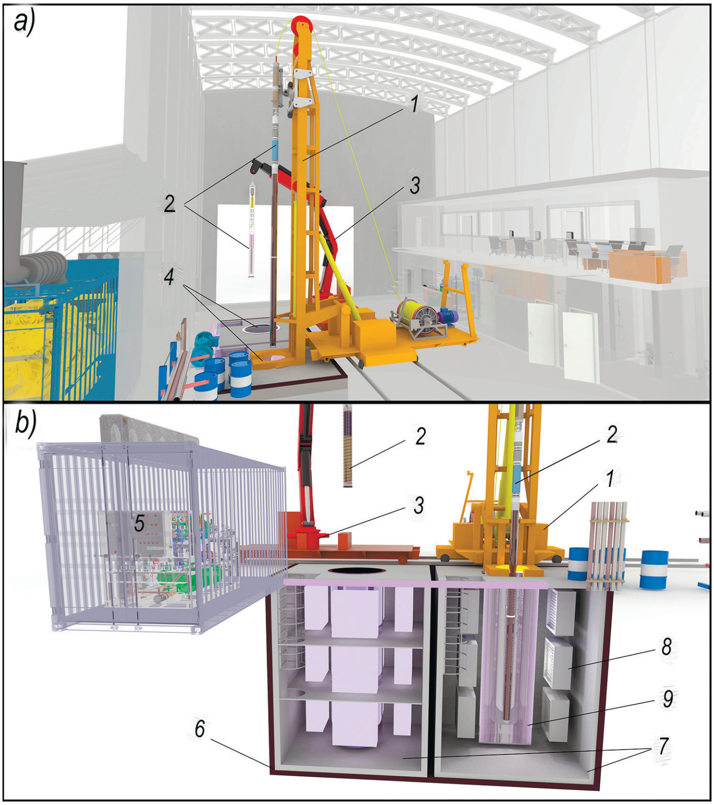

Fig. 1. Complex with two ice wells: *a* — main hall; *b* — climate equipment (*1* — drilling mast; *2* — tested drilling tools; *3* — hydraulic manipulator; *4* — collar of ice well; *5* — refrigeration and compressor equipment; *6* — hydro-heat-insulated pit; *7* — climate chambers; *8* — evaporators; *9* — ice well)

Рис. 1. Комплекс с двумя ледовыми скважинами: *а* — основной зал; *б* — климатическое оборудование (*1* — буровая мачта; *2* — испытываемые буровые снаряды; *3* — гидравлический манипулятор; *4* — устья ледяных скважин; *5* — холодильно-компрессорное оборудование; *6* — гидро-теплоизолированный котлован; *7* — климатические камеры; *8* — испарители; *9* — ледяная скважина)

13 m tall (Fig. 1). Below the building's zero level a 6 m deep hydro- and heat-insulated pit will be located. The building will include engineering and technical systems such as:

– power supply: power consumption up to 250 kW;

– water supply: centralized cold and hot water supply, with a flow rate of 5 to 10 m^3/h, through individual treatment facilities;

– ventilation system: supply and exhaust ventilation system, with heating of the air supplied in cold seasons;

– heating system: central heating system with a possibility to install heaters in lifting gates, entrance vestibules and mechanical workshops.

The complex is to be equipped with the following main equipment: ice wells, mounted in climate chambers installed in a hydro- and heat-insulated pit; refrigeration and compressor equipment; a drilling rig on a mobile platform; a hydraulic manipulator on a movable platform; process fluid tanks, and pumping equipment.

One climate chamber is designed to be able to maintain a constant operating temperature throughout the entire volume in the range from –2 °C to –70 °C, the second – with the ability to change the temperature in gradient in the heat-insulated sections of the chamber, allowing temperature control from +5 °C to –70 °C.

The chambers will be equipped with service hatches, ladders and local lighting for servicing the climate control equipment. The cooling system is individual for each chamber and built by using ozone-safe freons R404A and R23. Innovative technology for regulating the performance of refrigeration-compressor equipment enables smooth temperature regulation over a wide range.

Each climate chamber has its own autonomous power supply and control system, complete with an individual touch panel. The software allows saving test programs on a PC and uploading them to a controller, as well as using convenient functions for displaying information on the screen and printing. Remote access to the climate chambers is available, enabling real-time control of their settings from any user device.

The climate chambers' design and technical specifications were developed in collaboration with specialists at NPF REOM LLC in St. Petersburg. The drilling rig will be mounted on a platform with the possibility of longitudinal and transverse movement, making efficient use of the entire cross-sectional area of the ice well. The design of the drilling rig allows the use of two types of technologies: with cable-suspended drilling, and rotary drilling, depending on the research objectives.

The ice well complex fulfills the following tasks:

– study of ice destruction processes using mechanical and thermal drilling methods;

– conducting tests of technologies and technical devices for drilling glaciers and subglacial bedrock, as well as unsealing subglacial reservoirs and sampling water and sediments;

– testing geophysical equipment for ice boreholes;

– approbation of control systems for ice drilling;

– training of specialists for scientific research in Antarctica.

It should be noted that the establishment of a test center will address scientific and practical issues not only in Antarctica, but also in the Arctic region, allowing one to:

– investigate the processes related to permafrost thawing to ensure the stability of civil and industrial infrastructure foundations [25, 26];

– test permafrost drilling equipment to obtain undisturbed samples;

– conduct tests on mobile drilling equipment to sample core material from Arctic glaciers, icebergs and shelf ice to assess the safety of Northern Sea Route navigation and drilling platform operation [27, 28].

At the drilling complex of 5G borehole at Vostok station, modernization is planned, which involves replacing the main and auxiliary equipment.

The drilling complex was constructed during the 27th Soviet Antarctic Expedition on May 29, 1983 to drill borehole 4G, and later relocated to the site of borehole 5G. Since the start of its operation, the complex has undergone numerous modifications and now includes the following main components (Fig. 2):

– a drilling building, which consists of two mobile wagon-type units, installed on sleds and covered with heat-protective panels;

– a welded 12 m high drilling mast made of metal pipes, equipped with a system of blocks for tripping and drilling operations on a carrying cable;

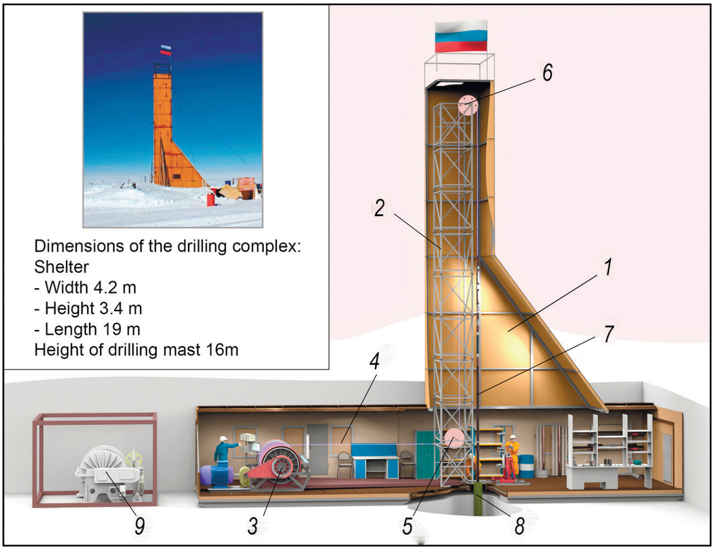

Fig. 2. Drilling complex of well 5G: *1* — drilling building; *2* — drilling mast; *3* — drilling winch with control panel; 4 — carrying cable; 5 — deflection roller; 6 — crown block roller; 7 — electromechanical drill KEMS-135; 8 — casing column; 9 — rewinder

Рис. 2. Буровой комплекс скважины 5Г: *1* — буровое здание; *2* — буровая мачта; *3* — буровая лебедка с пультом управления; *4* — грузонесущий кабель; *5* — отклоняющий ролик; *6* — кронблочный ролик; *7* — электромеханический колонковый снаряд КЭМС-135; *8* — обсадная колонна; *9* — перемоточное устройство

– a drilling winch with an 18,2 kW DC electric drive. On the winch drum a seven-core armored carrying cable is wound up, 4,100 m long and 17.5 mm in diameter. For equable laying of the cable on the winch drum, a cable layer on an endless screw is used with the possibility of manual adjustment;

– power supply system for working and auxiliary equipment;

– a control and monitoring system for tripping and drilling operations, including the main control panel (manufactured by Leningrad Mining Institute, 1984) and a special data collection module MSD-A (manufactured by AMT CJSC, St. Petersburg, Russia).

The borehole 5G consists of five branches (Fig. 3). Branch 5G-5 intersects several of the glacier layers studied, which differ in their structural and physical-mechanical characteristics:

– snow-firn layer (up to 100 m), represented by permeable layers of compacted snow turning into ice [29];

– meteoric ice (100 – 3539 m), the crystal size of which increases with depth [9]. This layer includes brittle ice (250 – 600 m), consisting of fragmented crystals [30], and ancient ice (3310 – 3539 m), the structure of which has been disrupted by ice flow anomalies;

– accreted (lake) ice with mineral inclusions (3539 – 3769.3 m) [31].The borehole is filled with a non-freezing drilling fluid – a mixture of Jet-1 aviation kerosene and F-141b freon, which has a density that compensates for the glacier pressure. The temperature and pressure of the drilling fluid change with the borehole depth [32]. According to caliper measurements of branch 5G-5, performed during the 69th Russian Antarctic Expedition (RAE), it was found that equipment with a diameter of 135 mm can be tested along the

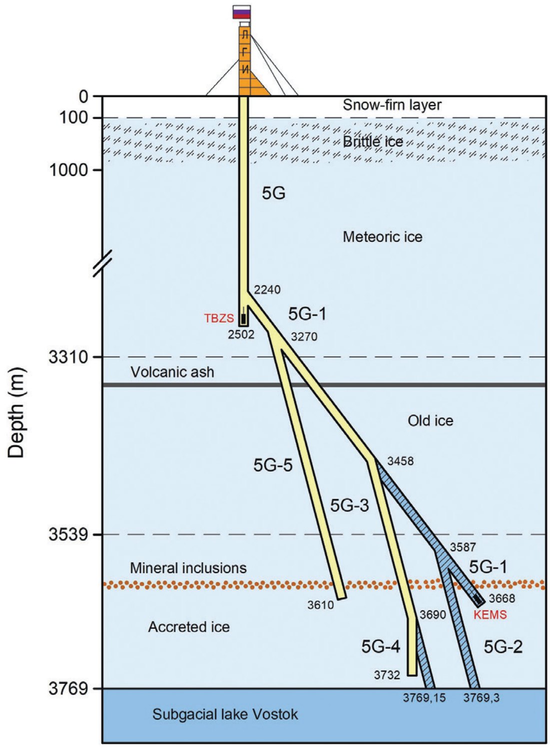

Fig. 3. Schematic representation of 5G multibranch borehole configuration. The shaded branches are filled with frozen lake Vostok water. The names of lost drills are shown by red inscriptions (adapted from [33])

Рис. 3. Схематическое представление конструкции многоствольной скважины 5Г. Заштрихованные участки заполнены замерзшей водой из озера Восток. Красные надписи обозначают наименования снарядов, оставленных в скважине (актуализировано из [33])

entire depth of the branch. Access to the other branches can only be gained by using a drilling tool with a controlled deviation in zenith and azimuth angles.

The deep drilling project at the 5G-5 branch was completed during the 69th RAE season, reaching a depth of 3610 m. Consequently, the borehole can be used to test technologies and technical devices for drilling glaciers in unique thermobaric conditions. However, the drilling complex main and auxiliary equipment is significantly worn out, necessitating modernization. This is the goal of the project "Comprehensive studies of subglacial Lake Vostok and paleoclimate around the area of Russian Antarctic station Vostok".

The modernization includes the replacement of:
– drilling winch and control system;
– carrying cable;
– deflection and crown block rollers of the drilling mast;
– rewinding the cable device;
– auxiliary equipment;

– inspection and repair of electrical supply systems.

The updated drilling winch with a capacity of 4 000m for a 17.5 mm carrying cable differs from the installed one in: a greater traction force (at least 80 kN); an improved electromechanical drive with a frequency control (40 kW power); automated control and monitoring systems for tripping operations and cable laying. For transpooling the carrying cable, a productive rewinder (winding speed 2 km/h) with a maximum pull force of 20 kN is to be used. The design and technical specifications of the winch and rewinder were provided by experts from of the Oktyabrsky Plant of Logging Equipment "VNIIGIS" LLC.

The new carrying cable for downhole equipment is KG (4 × 0.75 + 3 × 2 × 0.20) – 90 – 17, with a significant breaking force (at least 90 kN). It consists of four cores with a cross-section of 0.75 mm^2 and three twisted pairs with a cross-section of 0.20 mm^2. The carrying element of the cable is an UHMPE (ultra-high modulus polyethylene) thread, which is more resistant to mechanical impacts at low temperatures and in aggressive environments, has a higher strength and a lower specific gravity than cables wrapped in steel. The design and technical parameters of the carrying cable were provided by specialists from SKT Group LLC.

The proposed modernization will allow testing in the borehole:

– mechanical and thermal drills on a load-carrying cable at any depth interval, including equipment with a directional drilling control system;

– mechanical and thermal borehole reamers;

– technical devices for unsealing subglacial lakes from a borehole filled with a non-freezing fluid;

– drilling fluids;

– geophysical equipment for ice boreholes exploration;

– equipment for determining the physical and mechanical properties of ice;

– equipment for drilling new boreholes;

– delivery modules for research equipment of subglacial reservoirs;

– equipment for cleaning boreholes from mechanical impurities;

– equipment for eliminating accidents in boreholes;

– telemetry systems, sensors, etc.

3. Conclusions

Drilling operations on Antarctic glaciers necessitate extensive research and development aimed at understanding the processes of interaction between a drill and a glacier and testing the technical devices developed for drilling glaciers. For this purpose, teams of researchers from different countries create experimental stands with artificial ice. The primary distinction between these designs is the method used to model the glacier. Each method has advantages and disadvantages, but they all share one limitation: it is impossible to recreate the structure of atmospheric ice and thermobaric conditions in Antarctic boreholes.

The authors propose the conceptual project of a center for testing technologies and technical devices for glacier drilling. The Center will be located on two sites: on the educational and scientific testing ground "Sablino" of Saint-Petersburg Mining University in the Leningrad Region (Russia) and at the drilling complex 5G borehole at Vostok station in Antarctica. The realization of this project will allow conducting experimental research and testing, using both shallow artificial ice wells and deep borehole 5G in the Antarctic glacier.

The first stage of testing drilling equipment and technologies will be validating the proposed solutions on experimental stands that simulate future operating conditions under certain assumptions. The location of the stands at "Sablino" will allow conducting research all-year-round, as well as rapid adjustments to the designs of the devices and methods developed for conducting experiments.

In the second stage of the tests, the drilling equipment and technologies will be tested in a deep 5G borehole. This will enable testing the equipment's operability under thermobaric conditions and the specific ice structure of the Antarctic glacier.

The proposed approach to the realization of the project "A Center for testing technologies and technical devices for glacier drilling" will enable the most efficient and safe implementation of drilling operations in Antarctica.

Competing interests. The authors declare that there is no conflict of interest.

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Концептуальный проект центра испытаний технологий и технических средств бурения ледников

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Расширенный реферат

Реализация буровых проектов в Антарктиде требует проведения комплексных научно-исследовательских работ, направленных на изучение процессов, протекающих при бурении ледников. Важную роль в данных исследованиях играют экспериментальные стенды с искусственным ледовым массивом.

В результате проведенного обзора было установлено, что в большинстве случаев экспериментальные стенды и сооружения имеют ограничения в габаритах и функциональных возможностях и не могут воспроизвести реальных условий эксплуатации (низкие температуры, высокое давление, физико-механические свойства атмосферного льда) разрабатываемого уникального оборудования. Начало эксплуатации оборудования без проведения испытаний в реальных скважинных условиях повышает риски возникновения осложнений и аварий в процессе работ, вызванных недостатками в конструкции оборудования. Данные недостатки могут быть обнаружены только при проведении буровых работ непосредственно в Антарктиде, что может отрицательно сказаться на сроках реализации научно-исследовательских проектов.

Решением обозначенной проблемы является выстраивание новой последовательности испытаний работоспособности скважинного оборудования для условий Антарктиды:

1) Апробация концептуальных решений для технологий и технических средств в рамках малых экспериментальных стендов с использованием ледяных блоков.

2) Испытание полноразмерных рабочих прототипов в условиях ледяных скважин, на базе учебно-научного полигона «Саблино» Санкт-Петербургского горного университета (Ленинградская область, Россия). Конструкция скважин и их технологические возможности разработаны с учетом достоинств и недостатков предшествующих проектов. Климатические камеры, в которых расположены скважины, рассчитаны на регулирование температур в скважине в диапазоне от –2 °C до –70 °C. Предложенное в работе экспериментальное сооружение позволит проводить широкий комплекс испытаний оборудования для полярных условий.

3) Предварительные испытания оборудования в скважинных условиях на базе модернизированного бурового комплекса им. Б.Б. Кудряшова на станции Восток, Антарктида. Испытание разработанного оборудования в условиях скважины 5Г позволит оценить работу устройств в реальных условиях перед их внедрением в рабочую эксплуатацию.

Данный комплекс средств по испытанию оборудования будет способствовать решению множества научных и практических задач, связанных не только с исследованиями в Антарктиде, но и проектами, реализуемыми в арктических регионах.

Ключевые слова: Антарктида, бурение ледников, буровые технологии и оборудование, ледяные скважины, скважина 5Г, экспериментальный стенд

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