INNOVATION-BASED DEVELOPMENT OF THE MINERAL RESOURCES SECTOR: CHALLENGES AND PROSPECTS

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PROCEEDINGS OF THE XITH RUSSIAN-GERMAN RAW MATERIALS CONFERENCE, POTSDAM, GERMANY, 7–8 NOVEMBER 2018

United Nations
Educational, Scientific and
Cultural Organization

International Competence Centre
for Mining-Engineering Education
under the auspices of UNESCO

Rohstoff-Forum
Российско-Германский сырьевой форум

Innovation-Based Development of the Mineral Resources Sector: Challenges and Prospects

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CRC Press
Taylor & Francis Group
Boca Raton London New York Leiden

CRC Press is an imprint of the
Taylor & Francis Group, an **informa** business
A BALKEMA BOOK

CRC Press/Balkema is an imprint of the Taylor & Francis Group, an informa business

Typeset by V Publishing Solutions Pvt Ltd., Chennai, India

Published by: CRC Press/Balkema
Schipholweg 107C, 2316 XC Leiden, The Netherlands
e-mail: Pub.NL@taylorandfrancis.com
www.crcpress.com – www.taylorandfrancis.com

ISBN: 978-0-367-07726-6 (Hbk)
ISBN: 978-0-429-02238-8 (eBook)

Innovation-Based Development of the Mineral Resources Sector: Challenges and Prospects – Litvinenko (Ed.)
© 2019 Taylor & Francis Group, London, ISBN 978-0-367-07726-6

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Preface

Dear participants of the 11th Russian-German Raw materials conference,

Reliable supply of raw materials plays a core role in global economic growth. In this context the exhaustion of the sources of raw materials is one of the biggest challenges of the 21st century. Germany, whose mineral resources are rather limited, has traditionally maintained close ties with Russia as a source of raw materials for its economy. This bilateral partnership is now entering a new phase as the number of known sources of mineral resources is declining and joined efforts are needed to find more effective ways to extract and refine mineral resources, while simultaneously boosting energy efficiency and reducing losses during the processing of raw materials. A rapidly changing demand for raw materials in the course of the development of future technologies and digitisation makes a secure supply of raw materials all the more important. In addition, achieving the climate and sustainability goals agreed in international agreements also requires increased efforts in international raw materials cooperation.

A special role in solving these problems is played by research facilities of both countries, which have joined forces with business and politicians to develop and introduce new concepts for a long-term sustainable supply of raw materials.

The establishment of the Russian-German Raw Materials Forum has undoubtly been a most significant event for both Russia and Germany. At the 6th international public forum “Petersburg Dialog” that took place in Dresden in October 2006, in the presence of German chancellor Angela Merkel and Russian president Vladimir Putin a memorandum was signed to establish a permanent Russian-German forum on the issues of the use of raw materials. The establishment of the forum was initiated by Saint Petersburg Mining University and Freiberg University of Mining and Technology.

Saint Petersburg State Mining University and Freiberg University of Mining and Technology are leading higher education institutions in Russia and Germany, specializing in raw materials and, thus, they have a certain amount of responsibility at the national level, playing key roles in research cooperation between the two countries on raw materials and energy. The history of the world’s two oldest mining schools is closely intertwined: for many centuries now they have been sharing knowledge and high profile researchers.

Cooperation between the two schools began over 300 years ago when the Russian emperor Peter the Grate visited Saxony and soon after in 1739–1740 three young Russian scientists were dispatched by the Saint Petersburg Academy of Sciences to get training in mining in Freiberg, Saxony. One of the three young researchers was Mikhail Lomonosov. 25 years after Mikhail Lomonosov’s stay in Germany, in 1765, a mining academy was opened in Freiberg, and just 8 years later Russian empress Catherine II founded the Saint Petersburg Mining School, two events that initiated the development of mining science in Germany and Russia. Ever since Saint Petersburg Mining University and Freiberg University of Mining and Technology, the two educational institutions that for the first time in the world made mining a science, have been successfully cooperating in both research and education.

The Russian-German Raw Materials Forum is a communications venue and a factory of ideas which goal is to develop new approaches to effective use of energy, mineral and renewable natural resources and to initiate cooperation in the field of sustainability and environmental protection. One of the staples of the forum are the Russian-German Raw Materials Conferences that are held on a regular basis and give the participants an opportunity to meet, share their opinions and ideas, and thus make an important contribution to improving mutual understanding between Russia and Germany.

In recent years the Russian-German Raw Materials Forum has proved its effectiveness, as well as political and public significance, becoming an important venue for discussing the most pressing issues in relations between Russia and Germany, and not just in the field of mineral resources but also in such areas as foreign trade and cooperation in education and research. The number of participants in the Raw Materials Conferences is increasing every year, famous public and political figures take part as do heads of regions, researchers, representatives of major corporations and professional associations.

In the entire history of the Forum 10 Russian-German Raw Materials Conferences have been held:

Conference	**Name**	**Date, place**	**Number of participants**
1st Russian-German Raw materials conference	"Effective use of raw materials as a common goal for Germany and Russia".	October 2007 Wiesbaden, Germany	Over 150
2nd Russian-German Raw materials conference	"Development algorithms for raw materials markets"	March 2009 Saint Petersburg, Russia	About 180
3rd Russian-German Raw materials conference	"Reliable supply of raw materials"	March 2010 Dresden/Freiberg, Germany	Over 200 participants
4th Russian-German Raw materials conference	"Modernized partnership in the raw materials sector".	March 2011 Omsk, Russia	Over 300
5th Russian-German Raw materials conference	"Cooperation and innovations. 5 years of the Russian-German Raw materials forum"	April 2012 Nuremberg, Germany	Over 300
6th Russian-German Raw materials conference	Sustainable supply of raw materials in Russian-German Relations	April 2013 Khanty-Mansiysk, Russia	Over 200
7th Russian-German Raw materials conference	"Sustainable innovative raw materials partnership in modern conditions"	April 2014 Dresden, Germany	About 400
8th Russian-German Raw materials conference	"Russian-German cooperation in the raw materials sector: trust and reliability"	October 2015 Saint Petersburg, Russia	About 1000
9th Russian-German Raw materials conference	"Industrial production and mineral resources: Impact on the climate and environment"	November 2016 Dusseldorf, Germany	Over 500
10th Russian-German Raw materials conference	"Transparency and trust as a key element in sustainable Russian-German relations in the raw materials sector"	November 2017 Saint Petersburg, Russia	Over 1200

Five bilateral work groups have been set up to improve the goal-setting for the forum. Each work group is a permanent set of Russian-German participants specializing in a specific area of the raw materials economy, who spend a year discussing specific cooperation opportunities for the two countries to take advantage of. The working groups focus on environmental protection, recultivation, recycling, energy efficiency and digitisation.

It is vital that Russia and Germany expand cooperation on raw materials today in the light of the fact that, first, the partnership relations between Germany and Russia need to be improved further, including cooperation on effective use of mineral resources. Second, we need to refine the technologies available in mining and energy and deploy in production new technologies that are currently being developed in Russia and Germany. Third, it is of paramount importance that specific joint projects that can be economically beneficial for both countries be promoted and developed.

It is our earnest hope that the 11th conference of the Russian-German Raw Materials Forum that is to be held in Potsdam, the capital of Brandenburg (November 7–8, 2018), will demonstrate that both Russian and German colleagues are genuinely interested in building corporate relations, talking to each other as professionals, sharing experience and developing new approaches to further building bilateral relations. The conference will feature a discussion of the project to expand research and development cooperation between Russia and Germany on raw materials. It is certainly going to become a series step towards stabilization in relations, which is needed so much to improve energy security.

In order to promote relevant information to be discussed at the conference and popularize important problems in the raw materials sector, a decision was made for the first time in the history of the forum to compile and publish a digest of the materials of the conference. We hope that further down the road we will publish conference digests every year and that it will become a good tradition seeing how the forum accumulates a lot of very useful information about the current development trends in the global economy and the raw materials markets, the state of the environment and new technologies appearing in the industry, thus effectively meeting modern challenges.

We are very happy that today, despite the complex political situation in the world, the interest in the Russian-German Raw Materials Conference keeps growing, while the establishment of joint projects with Russian regions and professional cooperation in science and technology have enabled the Raw Materials Conference to become the main venue today for the dialog between the two countries in this area. The Raw Materials Forum fosters the development of our countries' raw materials cooperation into a sustainability partnership, which at the same time provides answers to the changing demand for raw materials for future technologies and other future issues.

We wish the participants of the 11th Russian-German Raw Materials Conference every success in anything they undertake!

Vladimir Litvinenko
Rector of Saint-Petersburg Mining University
Co-chairman of Russian-German Raw Materials Forum

Klaus Töpfer
Former Deputy Secretary-General of the United Nations
Co-chairman of Russian-German Raw Materials Forum

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Organizers

St. Petersburg Mining University,
St. Petersburg, Russia

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Mineral exploration and mining

Innovation-Based Development of the Mineral Resources Sector: Challenges and Prospects – Litvinenko (Ed.)

Russian developments of equipment and technology of deep hole drilling in ice

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ABSTRACT: This paper presents information about deep hole drilling in ice at Russian station Vostok. Borehole design and technical characteristics of downhole and surface borehole equipment are provided. On the basis of extensive data obtained in the process of 5G deep well drilling at station Vostok, processes running on the bottom of the hole, such as breaking–cutting of ice, bottom hole cleaning and carrying of drill cuttings out of the hole, cuttings collection in the filter are discussed. The factors having the greatest influence on ice drilling efficiency are considered. The process of penetrating to the subglacial lake Vostok is described in Conclusions and preliminary analysis of deep drilling results, ice sheet, ice core, drilling characteristics, the borehole are provided.

1 INTRODUCTION

Study of structure, material composition and dynamics of ice deposits in the polar regions of the Earth is impossible without drilling boreholes with full core sampling, which allows to carry out crystallo-morphological studies of ice from deep depths, geophysical exploration in holes, examination of ice chemical composition, content of oxygen and hydrogen isotopes, various inclusions (earth and space dust, volcanic ash, bacteria, spores of bacteria, etc.). In the long-term, hole drilling in glaciers and subglacial rock has great significance for geological exploration and further development of mineral deposits hidden under ice sheets.

The key objective of this paper is summing up Russian scientists' experience in developing technology and equipment for deep-hole drilling in ice.

Unique features of conditions in polar regions and in particular the Antarctic such as isolated location, impassable roads, extremely harsh climate bring forward very specific requirements to drilling equipment, technique, organization of operations and personnel training. Special requirements to drilling equipment are low power consumption, weight as low as practicable, high core quality.

Distinctive feature of drilling technology in ice is continuous coring, which is necessary for comprehensive scientific investigation and in this case round-trip operations are time consuming.

Given the demands, core-drilling method with cable-suspended drills has become a frequent practice. Application of flexible drill stem made it possible to reduce weight of surface drilling facilities in comparison to conventional drills due to use of light cable winches and to increase tripping speed.

Research-experimental and design work, aimed at development of technology and equipment for drilling in ice commenced in 1967 in Leningrad Mining Institute by the order of the Arctic and Antarctic Research Institute. By that time a number of countries achieved much progress in this field. A wide range of Russian scientists and polar explorers took part in inventing and introducing into practice technologies and equipment for drilling and borehole surveying in ice sheets. Among them are: S.S. Abyzev, N.I. Barkov, V.N. Bakhtyukov, K.V. Blinov, N.E. Bobin, V.N. Vasiliev, R.N. Vostretsov, L.K. Gorshkov, D.N. Gusev, D.N. Dmitriev, A.N. Dmitriev, E.A. Zagrivniy, V.M. Zubkov, E.S. Korotkevich, B.B. Kudryashov, A.V. Krasilev, V.Y. Lipenkov, N.N. Menshikov, S.V. Mitin, B.I. Slyusarev, G.N. Soloviev, G.K. Stepanov, P.G. Talalay, V.F. Fisenko, V.K. Chistyakov, B.M. Shashkin, A.M. Shkurko and others.

The most significant contribution was made by professor B.B. Kudryashov., who was an irreplaceable scientific coordinator of this research from 1967 till 2002.

Theoretic framework of thermal and mechanical ice crushing, methods of calculations of technological parameters of drilling operations have been developed. Selection of the formula of non-freezable drilling fluid to prevent well narrowing under rock pressure and natural ice temperature increasing with depth, which significantly changes ice viscoplastic properties has been substantiated. Fundamentally new cable-suspended semiautonomous electro-thermal and electro-mechanical drilling assemblies (TELGA, TBZS, KEMS), a complex of permanent and vehicular drilling equipment, automatic drilling control and monitoring systems were developed. Special techniques and geophysical research facilities for borehole surveying in hostile environment of polar glaciers have been worked out and mastered.

Differential characteristic of these operations is their strong practical focus. From after the 13th Soviet Antarctic Expedition (SAE, 1967), team members of the chair of Technology and technique of boreholes drilling, as well as members of other chairs of Saint Petersburg Mining Institute (SPSMI) took part in almost all Soviet and later Russian Antarctic expeditions (RAE) in both wintering and seasonal teams. In total 18 thousand kilometers were drilled with full ice coring in the Antarctic ice sheet (station Vostok, observatory Mirniy, glaciological profile Mirniy-Vostok1) and also in the glacier of Archipelago Severnaya Zemlya.

Giving credit to Boris Borisovich Kudryashobv's great contribution to the development of deep-hole drilling in ice technique, in summer 2013 a resolution was made at the meeting of the Advisory Council on the Antarctic Treaty to assign a status of a Historic site to the building of drilling complex named after professor Kudryashov at station Vostok in the Antarctic. In the seasonal period 59 RAE a memorial plate on awarding the status of the Historic site to the drilling complex of borehole 5G which was fastened to the wall of the drilling complex was delivered to station Vostok. This event is the recognition of Russian scientists' achievements in the field of study of Antarctic ice sheet and subglacial water bodies by International scientific community. A unique operation of penetrating to the subglacial lake Vostok, carried out by Russian researchers in February 2012 holds a special place. A new Historical monument will add to Antarctic monuments, which commemorate landmark events in exploration of the sixth continent. This will allow future generations to remember the outstanding researcher's name, Kudryashov Boris Borisovich, who from 1967 to 2002 was the leader of studies focused on development of technique and equipment for ice drilling.

The most significant are drilling operations at Russian inland station Vostok (78°28′ S., 106°48′ E.), situated 3488 meters above sea level on Antarctic ice sheet, overburden thickness of which is 3760 meters. At the time of the station foundation it was located close by the South geomagnetic pole which is the "pole of cold" of the Earth, it is characterized the by the lowest air temperature on meteorological record (–89,2°C).

Full-scale study including geophysics, glaciology, paleoclimatology, microbiology carried out at station Vostok is international in nature due to the uniqueness of data obtained in this part of the Earth, they specify unquestioned authority of national science in investigation of the Antarctic.

In relation to the discovery of a large subglacial lake in the area of station Vostok, one more exploration trend has been developed, i.e. exploration of this lake, which may become one of the Antarctic most significant projects of the 21 century.

2 DEEP-HOLE DRILLING AT STATION VOSTOK IN THE ANTARCTIC

Since 1970 drilling operations have been carried out at station Vostok. Before 1993 mainly thermo-drills were used. Our scientists (Kudryashov et al 1991; Kudryashov et al 1983; Pashkevich and Chistyakov, 1989) achieved success in their design and implementation. One of the objectives of this type of drilling is subglacial rock coring. That demanded a change—

over to mechanical drilling. That is why in 39 SAE season drilling facilities at station Vostok were re-equipped with the aim to continue operations with the electromechanical drilling assembly (Kudryashov et al., 2002; Vasiliev et al., 2007). Mechanical drilling in ice has obvious advantage over thermal drilling in much lesser power consumption, high drilling rate and better core quality. At present only mechanical drills are used for deep-hole drilling in ice (Augustin et al. 2002, 2007; Bentley and Koci, 2007; Fujii, et al., 2002; Gundestrup et al., 1984; Johnson et al., 2007; Shturmakov et al., 2007). In the result of lake Vostok discovery (Kapitsa et al., 1996; Ridley, et al., 1993) in water of which the hole was to penetrate, as well as, significant changes in mechanical properties of ice at the depth of 3000 meters require a reconsideration of the final objective, serious re-engineering and a new work plan (Kotlyakov et al 2013; Lukin and Vasiliev, 2014; Verkulich et al., 2002; Vasiliev et al., 2007).

3 SURFACE DRILLING FACILITIES

Surface drilling facilities for drilling in ice (Fig. 1) include the following primary members: a shelter, a winch, a control panel, a drill tower and mechanisms for drilling assembly maintenance, drilling support equipment and tools.

In Russian drilling facilities a mast is fixed to the floor and it can be levelled for the period of rig up and reconditioning. All surface maintenance operations of drilling assembly under a borehole construction are carried out when it is in vertical position. Special devices, which enable to carry out operations of detaching a coring tube and filters with cuttings from the drilling assembly as well as subassembly building up and dismantling are used.

A shelter protects drillers, instruments and equipment from external environment. Russian specialists use shelters made from thermal protection panels, which are also used, as a mast cover in harsh climatic conditions of the Antarctic. Both permanent shelters and portable drilling facilities are assembled on standard sled, which are used for supplies relocating during traverse. This type of shelters provides comfortable conditions for work both during seasonal and wintering periods when the temperature is –50°C.

Figure 1. Shelters at station Vostok.

4 DRILLS

4.1 *Thermal drill TELGA-14M (Fig. 2a) for drilling in dry holes*

A rotatory core bit is used for forming a bottom hole, melt water is removed from the bottom hole due to bottomhole air flow circulation. Circulating system of a drilling assembly consists of water suction tubes, a water tank, a thermal head and a turbo compressor, which creates vacuum in the water tank for water lifting. Gravity separation takes place due to sharp drop of flow rate in water tank as a result water accumulates in the low part of the tank while air is thrusted into the hole annulus spaces. When the core barrel or water tank is full, the assembly is detached from the hole bottom, blades of core catcher cut into the core, separate it from the hole bottom and it is kept in core barrel when lifted to the surface.

On the surface the core is removed from the core barrel and the water tank is discharged.

4.2 *Thermal drill TBZS (Fig. 2b)*

TBZS-152 thermal drill was successfully applied for deep hole drilling at station Vostok till 1993, permitting to obtain high quality core under high for thermal drilling effectiveness (Fig. 3).

The difference of TBZS from drills for dry hole drilling of TELGA type lies in the use of hole bottom circulation of drilling liquid for hole bottom dewatering, which is related to a number of features of construction of several drilling rig components. Control of drilling assembly performance is carried out on the basis of readings of downhole gauges and instruments, connected to heat elements and pump power circuits.

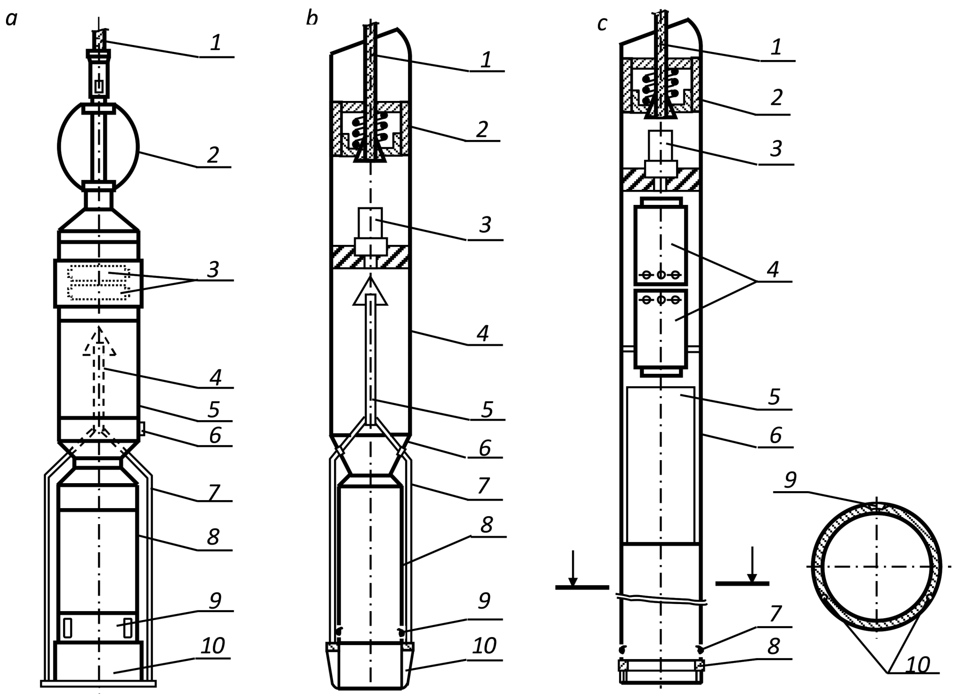

Figure 2. Designs of SPSMI thermal drills: *a* – **thermal drill TELGA-14**: 1 – cable, 2 – centering springs, 3 – vacuum pump, 4 – central water suction tube, 5 – water tank, 6 – valve, 7 – water suction tubes, 8 – core barrel, 9 – core catcher, 10 – thermal head; *b* – **thermal drill TBZS-152 M**: 1 – cable, 2 – cable termination, 3 – pump, 4 – water tank, 5 – central water suction tube, 6 – connector, 7 – water suction tubes, 8 – core barrel, 9 – core catcher, 10 – thermal head; *c* – **thermal drill TBS-112 VCh:** 1 – cable, 2 – cable termination, 3 – pump, 4 – electrical transformers, 5 – removable water tank, 6 – core barrel, 7 – core catcher, 8 – thermal head, 9 – electrical lines, 10 – water suction tubes.

In thermal drill TBS-112 VCh (Fig. 2c) to reduce power losses in the cable, power is fed to downhole according to the following scheme: "power source – step up transformer – cable – step down transformer – drill energy sinks". To reduce dimensions of step down transformers, installed in thermal drill, AC with 1250 Hz frequent currency is used.

The main difference when comparing TBS -112 VCh drill to TBZS-152M drill is the performance of the hole water removal system. When melt water gets into the tank, it freezes, as the water tank is not heated. On the surface the water tank with frozen water is removed from the assembly and is replaced by an empty one. As a result, energy bulk is saved, the quantity of cable conductors in carrying cable is reduced and consequently, its diameter narrows and weight is lightened.

4.3 *Cable-suspended electromechanical core drills*

For drilling deep holes filled with low temperature fluid, several designs of cable-suspended mechanical core drills with near-bottom fluid circulation, which are of various modifications of electric drills, have been developed in a number of countries. Rotation of rock cutting tool –a bit is driven by a motor coupled to a reducer, the assembly is lowered to the down-hole by gravity under free-run of a cable from the winch head.

The first electromechanical core drill for drilling deep holes filled with low temperature fluid was worked out and successfully used by US Army Cold Regions Research and Engineering Laboratory (CRREL) with the support of the National Research Fund.

The specific feature of CRREL drilling technique is that drilling cuttings, which must be removed from the hole, are dissolved in aqueous ethylene glycol solution. For this purpose concentrated glycol is sent downhole in a bailer on each coring run, the amount depending on the downhole temperature and volume of ice cuttings expected.

The solution gets the heat required for intensification of this process from the electric motor and also through work function of mechanical and hydraulic systems. Diluted solution of

Figure 3. Cores extracted by means of TBZS-152 (33 SAE).

ethylene glycol is removed on each return trip of the drill to the surface. The excess ethylene glycol solution in the bottom does not decompose the walls of the borehole as it has equilibrium concentration. It also does not mix with low temperature drilling fluid, which fills the hole over the downhole zone. Such technique permitted to decrease significantly the total length of the drill compared to a type in which crashed ice is accumulated in a special drill section.

For a long time the hole 2167 meters deep, which was bored with this drill in 1967 was the deepest hole in the world.

Impressive success in designing mechanical drills was achieved by Danish scientists from Geophysical Isotope Laboratory at the University of Copenhagen. Cable-suspended electromechanical drill ISTUK for coring deep fluid filled holes in low temperature ice sheets has a unique design.

The specific feature of the electromechanical drill is the use of a battery pack, which is charged during RIH/POOH operations. The run mean time being 6 minutes and mean length of a round trip- 2 hours (at borehole depth of 3500 meters) made it possible to use the cable 6, 4 mm in diameter.

So far, Danish specialists have drilled a number of deep holes in Greenland ice sheet with the depth of up to 3200 m.

A cable-suspended electromechanical drill was also designed in Laboratoire de Glaciologie et Géophysique de l'Environnement (LGGE) of the Centre National de la Recherche Scientifique, CNRS (Grenoble, France), which was tested on Adelie Land (Antarctic) in the season of 1981–1982. However, further operations in this area of work were suspended.

In early 1994 Japanese specialists worked out a drill which fundamentally differed from those used before. The drill was developed for drilling a deep borehole by Japanese Antarctic Research Expedition (JARE) at station Dome F (the Antarctic).

The design of the Japanese drill was used as the basis for developing drills for deep drilling in Greenland and Antarctic by the researchers of European community under the interrelated programs EPICA and NGRIP. For drilling in the Antarctica according to EPICA program LGGE developed a drill assembly. Researchers from Niels Bohr Institute of the University of Copenhagen (Denmark) who supervised work of LGGE, developed a drill under NGRIP program for drilling in Greenland.

In 1988 in Polar Ice Coring Office (PICO), University Alaska-Fairbanks (USA) an electromechanical drill PICO-5 for drilling deep holes was constructed. The drill consists of an outer non-rotating core barrel, inner drill head with core dogs, a core barrel, a cavity pump, a motor with a reducer, an electronics section, a transformer, an anti-torque system and cable locks. Schematic construction of this drill is similar to the European one. They differ in the pump design and dimensions. To produce bottom hole circulation in the drill a cavity pump with the pumping rate 130 l/min which is 3–4 times higher compared to other drills was used. For drilling subglacial rock an inner core barrel with less a diameter is attached to the end face of the core barrel.

In early 2000-s following these developments American specialists from the University of Wisconsin–Madison designed new drilling facilities with the DISCO drill, the kinematic scheme of this drill is similar to the Russian drill KEMS-132 developed for drilling in ice to the depth of 4000 m (Shturmakov, A.J et al, 2007). At a later stage the drill was equipped with a facility for deviation from the main hole for re-coring (Shturmakov, A.J et al, 2014).

4.4 *Core electromechanical drill KEMS-112 (Fig. 4)*

One of the main objectives of developing effective deep hole drilling technique was to construct a core electromechanical drill for full-depth drilling in glaciers with reaching the bedrocks and in particular for deep borehole completion at station Vostok, drilling of which was started with the use of thermal drills.

The field tests of this drill were carried out in 1984, 1986 and 1988 at Kupol Vavilova (Severnaya Zemlya Archipelago) where in 1988 a borehole 461 m deep was produced. At the depth of 457 m the drill with a standard coring bit SA-1penetrated subglacial rocks. The

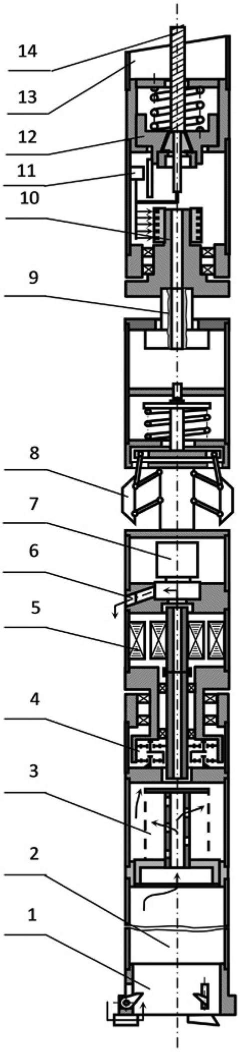

Figure 4. Schematic of core electromechanical drill KEMS-132: *1* – drill head; *2* – core barrel; *3* – chip chamber; *4* – gear reducer; *5* – electric motor; *6* – drilling fluid sensor; *7* – pump; *8* – anti-torque system; *9* – hammer; *10* – current collector; *11* – down-hole load sensor; *12* – cable termination; *13* – top chip chamber; *14* – cable.

Figure 5. Subglacial core samples from Vavilov glacier.

average rate of penetration to frozen ice-laid deposits and rock which consisted of frozen clay containing lots of fragmentary material of sedimentary origin was 1,5 m/h. A hole 4 m deep was drilled in subglacial rocks, the core recovery was 100% (Fig. 5).

For drilling in hole 5G diameters of a core barrel and a drill head were increased.

Basic equipment of core electromechanical drill (Fig. 4) comprises: drill head *1*, core barrel *2*, chip camber with a screen *3,* gear reducer *4,* electric drive motor *5,* pump *6* which produces reverse circulation of drilling fluid, anti-torque system *7,* hammer *8,* electric closet *9* with cable end *11* for cable termination *10*. The function of the electromechanical drill is as follows. Electric motor rotator *5* transmits rotation through the gear box *4* to the core barrel with the drill head *1.* Cuttings are carried to the chip camber *3* by a flow of drilling fluid and remain in the chip filter. Drilling fluid moving up the central holes of the reducer shafts and drive motor is thrusted out to the annulus space by the pump *6*.

Main characteristics of KEMS-132 drill.

Diameter of drill head, mm:	
OD	132–138
ID	99–106
They enable the upper part of the drill to rotate during the drilling operation	
Length of core barrel, m	3
Drive motor:	
Input voltage, Volt	~220
Rotor speed rpm	2800
Drill head revolutions R.p.m.	120–220
Penetration rate, m/h;	
In ice	up to 20
In subglacial rocks	up to 1, 5
Overall length, m	13
Weight, kg	240

5 DRILLING LIQUID

Various types of aviation fuel are used as the main component of drilling fluids for ice deep drilling. Due to low density of lp gas fuels when pumped into the borehole drilled in ice, full balance of ice sheet pressure is not ensured. For weighting of liquid column various additives of chloro-fluorocarbons (Freon-11, Freon-141b) and ethylene hydrocarbons (perchloroethylene, ethylene trichloride) are used in drilling practice.

At present aviation fuel Jet A-1 is the most commonly used jet fuel, it is produced in a number of European countries (Great Britain, Germany, Switzerland) and in the USA. Aviation fuel JP-8 is produced in the USA and it is very similar in properties to Jet A-1.

For deep drilling at temperature below −30°C a composition of cryogen carbon based drilling liquid was worked out in Leningrad Mining Institute. Aviation fuel TS-1 as per GOST standard 102227-86 was chosen as a carbon base, Freon-11 (CFC-11) was used as a weighting material. When kerosene is mixed with Freon, mixture density decreases simultaneously with the increase of mixture viscosity that is good for the drill circulation system.

In 1987 in Montreal and in 1990 in London International Protocols were adopted, according to which production of chloro-fluorocarbons, which deplete ozone layer was cut by 50% by 1995 and was completely curtailed by 2000. In view of this since 1995 dichlorofluoroethane (HCFC 141b) has been used instead of CFC-11 at station Vostok.

Mechanical ice drilling has the advantage over thermal drilling by much lesser power consumption, higher rate of penetration and better core quality. At present time only mechanical drills are used for deep ice drilling.

Drilling operations at station Vostok began in 1970. Several holes were drilled and by the time of their completion they were the deepest in the world (Fig. 6). Till 1994 only thermal drills were used, but when borehole 5G reached the depth of 2755 meters they were replaced by electromechanical drills.

Borehole No. 1G (Fig. 6)

In 1970 during the 15th SAE drilling of the first deep hole using the thermal drill TELGA-14 began. In May 1972 hole No. 1G reached 952, 5 m., which is up to now is considered to be the world's record in drilling the deepest dry hole in ice. Drilling of that hole stopped because the cable was ruptured during one of the runs and a new hole No.1G-2b was started. Drilling stopped at the depth of 905 m. due to a number of mishaps in the 19 th SAE in 1974. The main problem was the fast hole narrowing due to ice rock pressure, which could lead to getting the drill stuck in the hole during the round trips.

Borehole No. 3G (Fig. 6)

Taking into account the experience gained during borehole No.1G drilling, a decision was made to fill the holes with low temperature liquids to resist ice rock pressure. After several unsuccessful efforts to start drilling deep hole No.2G using thermal drill TBZS-152 in the 20th, 21st and 22th SAE drilling operations at station Vostok were suspended for a year with the purpose to conduct analysis of obtained results, to improve drilling technique with the use of drilling fluid and to modernize the drill. In the course of this work major changes were introduced into the design of several drill components and a system of control and management of the drill was developed.

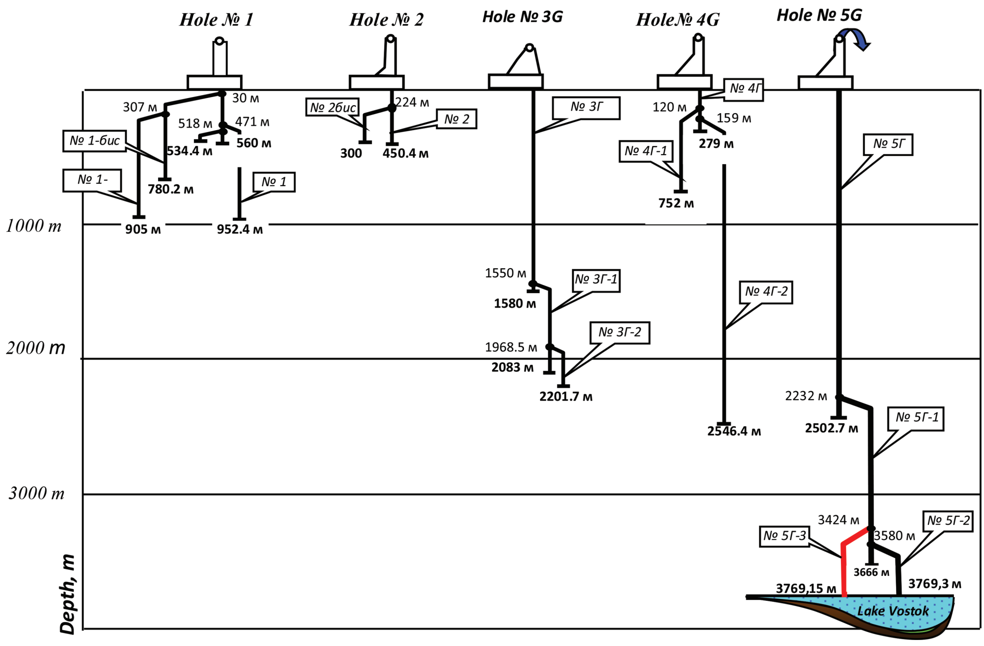

Figure 6. Schematic of deep holes at Vostok station.

In 1980 in the 25th SAE drilling of a deep hole No.3 GB commenced using the upgraded thermal drill TELGA -14M. Up to the depth of 112 m thermal drill TELGA-14 m was used, after that drilling continued using drill TBZS-152M. By the end of the 25th SAE, under single shift work the hole reached the depth of 1351 m and during the 26th SAE it reached the depth of 1501 m. During that expedition a small amount of densifier CFC-11 was used for the first time.

In the 26th SAE drilling of hole No. 3G at the depth of 1501 m proceeded using a high frequency drill TBS-112VCh. In the 30th SAE the hole reached the unprecedented for that time depth of 2202 m., and at the time of the 31st SAE at the depth of 1943 m an accident happened, a cable tore away from the cable termination and further activity in hole No.3G was stopped.

Borehole No. 4G (Fig. 6)

On July 3, 1983 a construction a new drilling complex for hole No. 4G was started. It was completed in the 28th RAE. The depth of 120 m was reached using a TELGA-14M thermal drill, then drilling was continued with another thermal drill, TBZS-152–2M, for fluid filled holes.

By the middle of the 34th RAE winter season after a series of accidents which resulted in deviation works from the emergency holes, hole No.4G reached 2428 m and drilling was continued with the electromechanical drill KEMS-112. At 2546 m the drill stuck in the bottom of the hole. The cable was ruptured on the surface during the attempt to eliminate the damage caused by the accident and the hole was completely lost. The cause of the accident became clear only during the 40th RAE when drilling hole No.5G by a mechanical drill.

Borehole No. 5G

Drilling of hole No.5G was started in the 35th SAE (1990) using a TELGA and TBZS thermal drills (Fig. 7). Hole No.5G reached 2755 m in the 38th RAE (1993).

Drilling of the hole No.5G continued using the electromechanical drill from the depth of 2755 m during the 40th RAE (1995) and reached 3109 m without complications. Then in the course of the 41st, 42 nd and 43rd RAE (1995–1996, 1996–1997, and 1997–1998) hole No. 5 g-1 was driven within in the depth interval from 3109 m to 3623 m. In 1998 after season works drilling was suspended for 8 years and was resumed only in January 2005 in the 51st RAE season, when 3650 m depth was reached. Drilling operations were stopped due to the necessity to develop ecologically clean technology in relation to the penetration to a subglacial lake Vostok, existence of which was proved in the mid- 90 s.

Considerable success achieved when drilling hole No.5G allowed to obtain important results in paleoclimate studies (Jouzel, J.et al., 1999). It is attributed to the period 1992–1998 when operations were conducted by a joint Russian-French-US project. The French rendered great support in providing expensive technical equipment and supplies. They placed at Russian drillers' disposal a casing string, cable and drilling liquid densifier (Freon 141b). In the Laboratory of Glaciology and Geophysics of the Environment (Grenoble) Russian researchers together with French colleagues tested components of drilling equipment manufactured at French plants and prepared for operations at station Vostok.

The Americans provided transportation of all Russian members of polar expeditions who worked at station Vostok, including rotation of staff working at the station.

In addition, French and American colleagues participated in seasonal works and examined ice extracted from the hole (Fig. 8).

130 m were left to be drilled above the lake according to preliminary calculation before drilling stoppage. Idle time was connected to logistics and technical challenges faced by the Russian Antarctic expedition at that period. Despite the long period of inactivity no deformations of the hole walls were observed owing to practically full compensation of ice overburden pressure by the pressure of drilling liquid standing column.

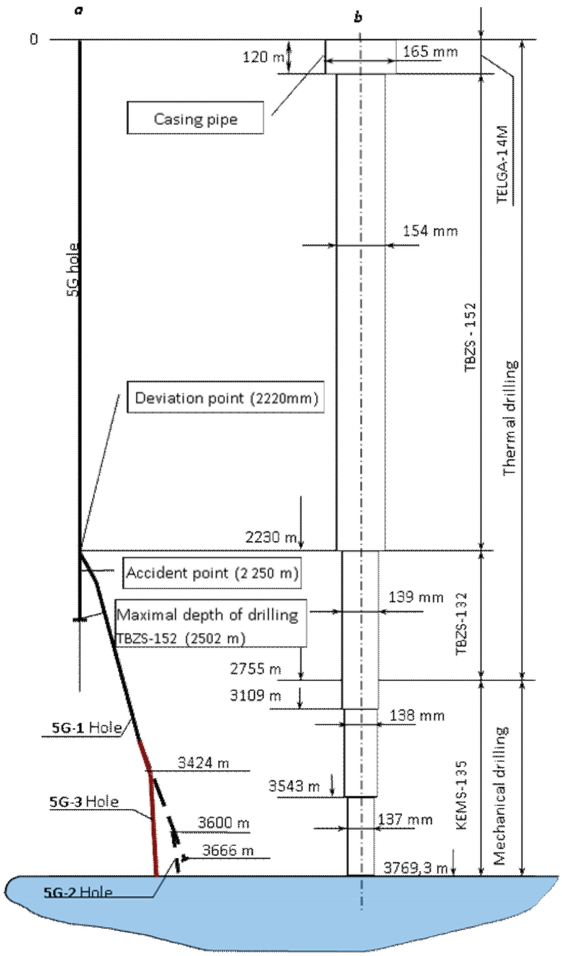

Figure 7. Schematic of hole No.5G.

Figure 8. Members of the International team at station Vostok.

On February 5, 2012 in the season of the 57th RAE the subglacial lake Vostok was unsealed at the depth of 3769, 3 m for the first time. In the course of the next three seasons the 58th, 59th and 60th RAE a new offset hole was started after freezing of water. Initial inclination of a new hole was about 0, 15 degrees. At the depth of 3443 m the holes channeled off and the full core of glacial ice was obtained. The hole below 3443 m was designated hole No.5G-3. Inclination angle at the depth of 3769 m is close to 3 degrees, which is 2 degrees less than the angle of inclination of hole No. 5G-2.

The total volume of drilling liquid (mixture of aviation fuel TS-1 and Freon F-141b) in the hole is 60 m^3. As of January 29, 2015 the level of drilling liquid was at 44 m and its mean density was 906 kg/m^3.

When drilling deep holes both in the Antarctic and in Greenland researchers ran into serious troubles at the depths over 2500 m and at 3000 m complications were so serious that drilling operations almost came to a full. This phenomenon was even called "a problem of drilling in warm ice", because with the increase of depth temperature increases as well. The illustration of such complications is the decrease of drilling a hole per a run at Dom C in terms of EPICA project. Decrease of a drilling run began as deep as 2 500 m, then with depth growth the rate of decrease of a drilling run increased and at 3000 drilling almost stopped.

The analysis of the situation showed that due to high temperature ice becomes very elastic and stuck to the cutters and body of the drill head. In our view, arising challenges in drilling may not be attributed only to the increase of ice temperature. Analysis of the complications, which arose during drilling operations showed a clear connection between the change of ice crystal lattice and its physical-mechanical properties.

All sections of the hole where problems of drilling were registered correspond to coring intervals formed by relatively coarsely crystalline ice (Fig. 9). There is a clear correlation between the run length and crystal sizes. Roughly from the depth of 3480 m sizes of crystals are about 20 mm, and in drilling a stable tendency to full cessation of hole making process has begun to show.

With growth of average size crystals at a constant rotation of the drill head and mechanical drilling rate the coarseness of cuttings decreases which is conductive to adhesion of ice cuttings, abrupt increase of hydraulic friction in the of chip chamber filter and reduce in drilling fuel consumption.

The solution to the problem was found by the end of seasonal work in the 43th RAE (January 1998), but due to stoppage of drilling which was necessary to develop the technique of penetration to subglacial lake Vostok by means of modernized drill, drilling operations were resumed only in the 56 th RAE (January 2011),

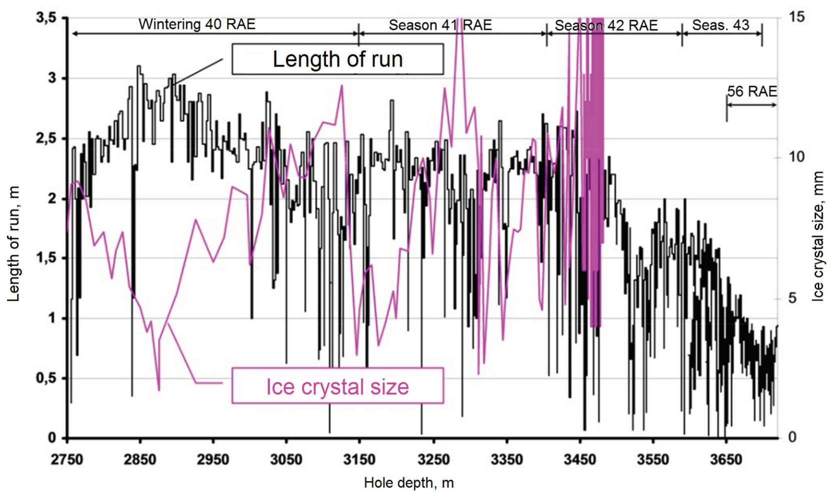

Figure 9. Results of mechanical drilling of hole No.5G-1.

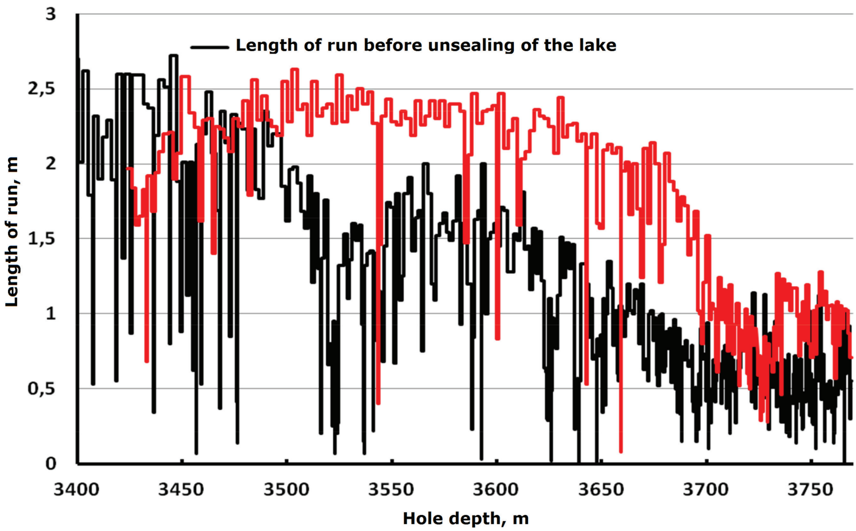

Figure 10. Length of run in holes No. 5G-1, 5G-2 and 5G-3.

Testing of the upgraded drill was carried out in the process of re-drilling when the water which entered the borehole during the first penetration to lake Vostok had frozen. As is seen on graph 10 the drilling process stabilized under twofold increase of the runs.

Drilling of hole No.5G-3 was successfully completed on January 25, 2015 when repeated penetration to lake Vostok at the depth of 3769,5 m was performed.

7 PENETRATION TO VOSTOK SUBGLACIAL LAKE

In 2011 the Code of conducting for the exploration and research of subglacial aquatic environments was adopted.

By that time it was known about two more projects on penetration to subglacial water bodies announced by the British and American researchers in which it was intended to use hot –water drilling technology.

The British project is on penetrating and studying lake Ellsworth, which is located 3000 m below the glacier.

Maximal depth of the lake is 150 m, the surface temperature of the glacier is –32°C. Up to the schedule, drilling operations and sampling of water and bottom deposits were to be completed in the season of 2012–2013. However, due to serious technical problems the project was not implemented.

The American project Wissard stipulated the study of subglacial lake Whillans which is in the hydrological system under the ice-covered stream Williams. The glacier height above the lake is 700 m, the water body depth is about 8 m. Project activities were successfully executed in the season of 2013.

In 1999 development of the technique for the penetration to subgalcial lake Vostok was begun by the scientists of AARI and Mining University on an assignment of the Ministry of Education and Science of the Russian Federation following the termination of drilling hole No.5G at the depth of 3623 m in January 1998. In 2001 the developed technology was approved by the RF Ecology expert panel. Russian technology was subject to strong criticism on the part of International research community, when the finalized document of the Overall assessment of impact on environment was presented to Antarctic Treaty Consultative Meting in 2010, International community had no objections against penetration to lake Vostok.

The worked out technology was based on the fact, that the interfacial pressure of water with the glacier foot equals the hydrostatic pressure of overburden ice. The density of drilling fluid is less than water density and they are not miscible. In providing less pressure of water column at the bottom than water pressure on the surface of the lake it was meant that water would to enter the hole.

The presented project intended only unsealing the lake without penetration to the lake water for its study. The main objective was to substantiate propositions on which the developed technology about equality of water pressure on the interface water-ice and the overburden ice hydrostatic pressure was based.

The first penetration to subglacial lake Vostok took place at the depth of 3769, 5 m on February 5, 2012.

Before the penetration drilling fluid pressure at the bottom was approximately –0, 2 MPa less than the hydrostatic pressure of ice according to graph 1 (Fig. 1). To ensure the balance at the hole bottom at the time of unsealing the lake it was enough for the fluid to rise to around 20 m. The fluid level was to stop at the depth of 5 m, and the difference pressure in the hole was to correspond to the data in graph 2 (Fig. 11). As the second drilling operation showed, after water that entered the hole got frozen, its flow into the hole did not stop, it kept on running into the hole.

Water rose to 3200 m then it dropped down to 3400 m, after that the pressure in the hole on the surface of the lake was equal to water pressure in the lake and the process stopped. Fluctuation of water level, which entered the hole, is accounted to the underbalanced zone, which is formed when the drill is pulled out. When hoisting speed is 0, 3 m/s, the pressure under the drill may drop by 0,2 MPa and as the hole is open at the bottom, water will flow into it. That is why water rose into the hole above that static equilibrium level by about 200 meters. When the drill reached 3000 m drop of pressure caused by its movement reduced, due to the increase of the hole diameter and when the drill entered the oversize hole at the depth of 2250 m drop of pressure became insignificant. Under the decrease of pressure difference water level started to go down slowly concurrently restoring equilibrium in the hole. A portion of water, which entered the hole re-entered the lake. Borehole condition stabilized and water, which entered the hole started to freeze after the drill was pulled up to the surface. The fact that several ice plugs mixed with Freon hydrate were formed in the hole and blocked off the hole cross section indicates that water went down rather slowly. The walls of the hole were covered by a layer of frozen water, the thickness of which gradually grew with the increase of

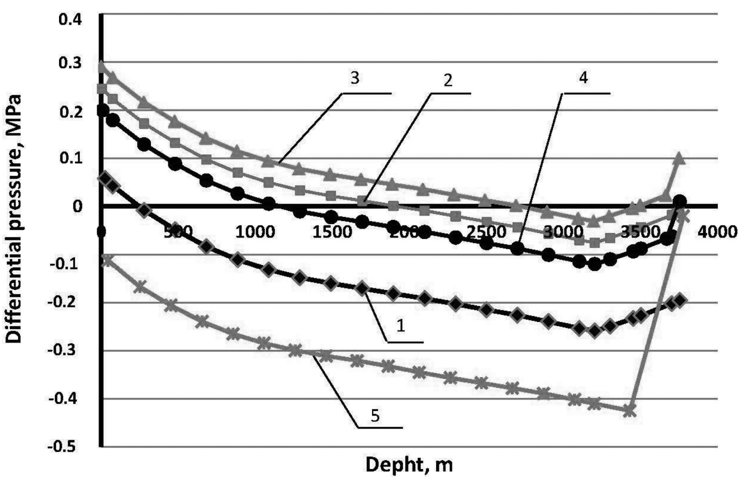

Figure 11. Diagrams of differential pressure in the borehole during unsealing the lake Vostok 1 – At the moment of unsealing the lake; 2 – At the beginning of liquid pouring out from the borehole; 3 – At the end of liquid pouring out from the borehole 4 – Fluid level dropped by 10 meters 5 – Diagrams of differential pressure after the cable was pulled out from the borehole.

the depth (Fig. 12a). At the depth of about 3400 m the thickness of that cover was approximately 25–28 mm (Fig. 12b).

The results of the first penetration objectively testify that water pressure on the surface coincides with the hydrostatic pressure of ice.

On January 25, 2015 subglacial lake Vostok was re-entered for the second time at the depth of 3769,5 m (Figs. 13 and 14) after re-entry drilling at the 3200 m depth.

Taking into account the previous experience, differential pressure –2, 2 MPa was created on the hole bottom. In accordance with this differential pressure water was to enter the hole at the height of 72 m.

As specified in calculations minimum 10 upper meters of the water column were to freeze in 5 days. That is why on January 30, 2015 drilling was resumed.

The surface of the frozen water was at the depth of 3696,7 m, i.e. it rose in the hole to the height of 72,5 m.

At the depth of 3709 m subglacial lake water entered the borehole and down hole performance ceased.

The first meter of obtained core consisted of frozen water, then there were several meters of white opaque core and the last meter consisted of frozen water (Fig. 14).

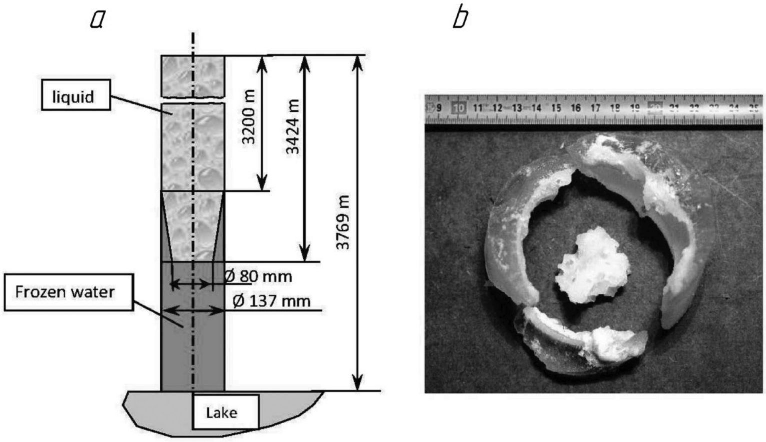

Figure 12. Scheme of the well 5G after the freezing of lake water a – Scheme of the well; b – Ice core from the 3424 m. depth.

Figure 13. Drill head after the second penetration to the lake.

Figure 14. Cores extracted after the second unsealing of the lake.

It is possible to reconstruct the process of water ascent into the hole during the lake unsealing through the obtained core.

At the beginning water flows up very quickly in the clearance between the drill and the borehole walls, it actively merges into drilling fluid and lifts above the drill to approximately 10 m, after that the drill penetrates this interfusion and mixes it further. The result is emulsification, which entraps water dropping from the drill during its further hoisting. Emulsification is related to the presence of Freon in kerosene oil. In addition, a large amount of hydrates of Freon appears in the emulsion due to a vast contact area of water and drilling liquid and this hydrate plug was frozen before the drill was pulled out of the hole.

The results of the second penetration to the lake allow us to conclude, that we cannot provide performance capacity of the hole under direct contact of drilling liquid with lake water as the hole will be sealed long before lowering research equipment into it. Besides hydrates of Freon will develop actively even when using a buffer layer of ecologically clean liquid (silicone fluid), through which the research equipment will pass but with drilling liquid stuck to its surface during tripping down the hole it will contaminate the lake water.

8 CONCLUSIONS

When deep hole drilling at station Vostok a large body of data was obtained, which will allow to simulate accurately the processes going in the hole both during drilling operations and unsealing subglacial water bodies. Updating of drilling technological parameters and changes introduced into the design of the drill make it possible to be sure that when drilling at the depths over 300 m the performance efficiency may be the same as at higher levels. These conclusions are clearly proved by the results of re-drilling of hole No.5G after freezing of water which entered it.

In the course of work the main factors influencing efficiency of drilling operations were defined and methods of overcoming complications were demonstrated. As the result, development of the basic framework of drilling technique in ice can be considered completed.

Based on the data on unsealing the subglacial lake Vostok it can be stated that the pressure on the surface of the lake corresponds to ice hydrostatic pressure and the method of measuring pressure in drilling liquid and its control facilitates safety of lake unsealing operations.

Studies of lake Vostok when unsealed by a hole filled with a mixture of kerosene and Freon cannot be performed with ensuring all requirements of ecological safety.

To facilitate ecological safety of studying lake Vostok, either complete substitution of drilling liquid or drilling of a new access borehole with ecologically friendly drilling liquid is required.

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