International Journal of Applied Engineering Research ISSN 0973-4562 Volume 12, Number 5 (2017) pp. 561-566

Inertial Mechanical Reamer for Borehole 5G-3 Conditioning for Penetration into Subglacial Lake Vostok

Nikolai I. Vasilev, Alexey V. Bolshunov and Sergei A. Ignatiev

St. Petersburg Mining University,
21 Line, 2, Vasilyevsky Island, 199106 St. Petersburg, Russia.

Abstract
The paper reviews challenges associated with developing a technology for penetration into Subglacial Lake Vostok in Antarctica. It outlines prerequisites indispensable for further surveys of Subglacial Lake Vostok using Borehole 5G-3 and describes a technology that ensures compliance with these requirements. Design elements of the drilling assembly needed to implement this technology are described. Designing goals were defined for mechanical reamers and a design of inertial mechanical reamer was studied in details.

Keywords: Antarctica, Lake Vostok, Borehole 5G-3, penetration technology, inertial mechanical reamer

INTRODUCTION

Subglacial Lake Vostok was penetrated for the first time ever on February 05th, 2012 at 8.25 pm Moscow Time [1]. Penetration was performed by specialists of the St. Petersburg State Mining University and the Arctic and Antarctic Research Institute. The borehole depth measured as the length of the obtained ice core was 3769.3 m.

Lake Vostok is the largest subglacial lake in Antarctica [2, 3, 4] and the main trends for its further research are as follows [1]:

- Research into the biodiversity of flora and fauna that inhabit such natural objects;
- Studies evolutionary patterns in development of living organisms that have been isolated from the Earth atmosphere for several millions of years;
- Collection of bottom samples with the purpose of studying the Earth crust below the Antarctic ice shield to assess its composition and morphology before the glaciation process started in the South Pole region (30-40 mln. years ago);
- Fine-tuning of technologies and engineering solutions in terrestrial conditions for their further application in space explorations aiming to find life forms on other objects of the solar system.

Lake Vostok being a unique natural system, no further investigations are possible without observations of the following key conditions:

- Environmentally safe way of work execution;
- Stability of the borehole interval filled with the lake water, and prevention of delivery vehicle freezing on to its walls;
- Reliability and trouble-free operation of all arrangements and systems used to deliver the research tools and instruments into the lake.

A borehole conditioning technology was developed for Lake Vostok penetration using Borehole 5G-3 in order to meet the requirements mentioned above. This technology envisages the following stages (Figure 1).

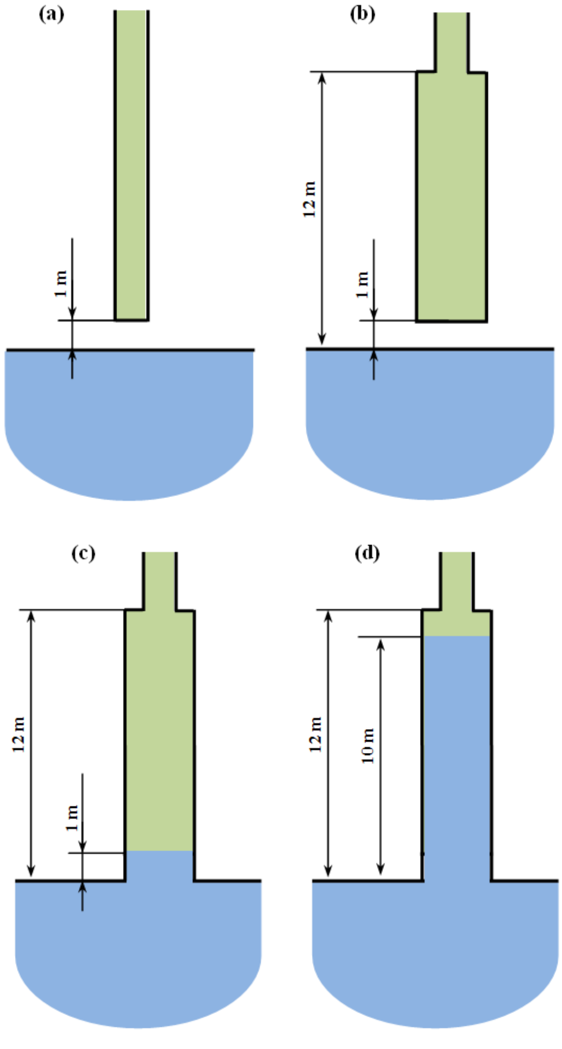


Figure 1. Borehole reaming technology for penetration into Lake Vostok:
a – borehole drilling with the drilling assembly; b – borehole reaming with a mechanical reaming assembly; c – borehole reaming with a thermal reaming assembly; d – ingress of the lake water into the borehole

The first stage assumes drilling a 138-mm borehole down to the depth of 1 meter to the borehole-Lake Vostok boundary using a regular drilling assembly (Figure 1, a).

The second stage consists in reaming the borehole up to 300 mm in diameter at the depth interval from 1 to 12 m from the borehole-Lake Vostok boundary (Figure 1, b). It is intended to use a mechanical reamer to perform this operation.

Borehole reaming during the third stage is done with a thermal reamer that penetrates through the final one-meter-thick ice plug and opens the borehole into the subglacial lake. This approach enhances the environmental safety of the operation (Figure 1, c).

The final forth stage involves a controlled ingress of the lake water into the reamed borehole up to the height of 10 m above the lake surface, which is required to secure environmental safety of further operations (Figure 1, d).

Subsequently, a delivery vehicle with a research module (Figure 2) is run into the borehole pre-conditioned for penetration into Lake Vostok, and investigations of the subglacial lake are performed as described in [5].

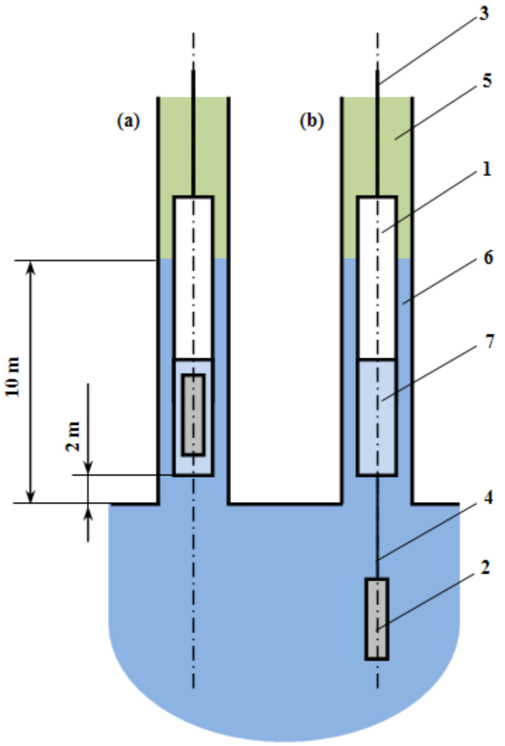


Figure 2. Layout of the delivery vehicle inside Borehole 5G-3 in transport position (a) and operating position (b):
1 – delivery vehicle; 2 – research module; 3 – carrying cable; 4 – carrying line; 5 – filling fluid; 6 – lake water; 7 – winch cabinet filled with distilled water.

Task Definition for Designing of Reamer Assemblies

A mechanical and a thermal reamers are required to increase the diameter of Borehole 5G-3 up to 300 mm.

Reviews of commercially available mechanical reamers as well as a patent search among research developments have proven that non of the existing reamer designs meets completely all the present operating requirements. One of the major drawbacks in the studied reamer designs is the complexity of arrangement used to convert the reamer from the transport into the operating mode and backwards, which reduces the reliability of this transformation.

Thus, a task was formulated to design a mechanical reamer that would meet the following requirements:

- Simple design;
- Ease of assembly to and disassembly from the drilling assembly;
- Diameter in the transport mode: 127 mm;
- Borehole reaming up to 300 mm;
- Secure arrangement to convert the reamer from the transport into the operating mode and backwards.

The thermal reamer design is assumed to be based on design concepts that have been used in thermal drilling tools successfully implemented in borehole drilling in glaciers [6, 7, 8, 9].

DESIGN AND OPERATING PRINCIPALS OF INERTIAL MECHANICAL REAMERS

Inertial reamers use the centrifugal inertial force created by the drilling tool rotation for spudding and rock mass destruction. The centrifugal inertial force makes holders with the cutting tools deviate from the drill string rotation axis. At least three cutting tool holders should be used in order to centralize the reamer inside the borehole.

Mechanical inertial reamer (Figure 3) consists of a hollow housing (1) which walls have three continuous axial slots (2) located at 120º relative to each other.

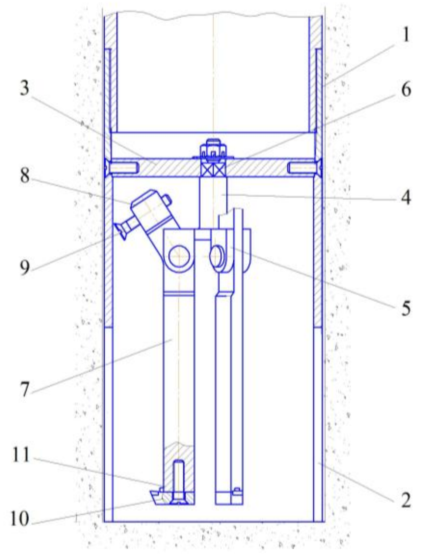


Figure 3. Mechanical inertial reamer in transport position

A support (3) is fixed inside housing (1). The support is designed as a 118-mm disk with a centrally located square hole (10 mm x 10 mm) and four 30-mm openings to evacuate the drill cuttings formed in the reaming process. Support (3) has a yoke (4) with eye ends (5) located at the same angles as the axial slots (2) of the housing, i.e. 120º. Pin (6) of yoke (4) is square in cross section with the side width of 10 mm, which prevents its axial turning against support (3) .

Cutting tool holders (7) are hinge-mounted in eye ends (5) of the yoke and can freely rotate relative to the hinge axes. The reamer assembly has three cutting tool holders (7), which secures its self-alignment in the borehole. The cutting tool holders (7) are rectangular in cross-section (18 mm x 12 mm). Upper ends (8) of cutting tool holders (7) are located at 33º relative to the lower part and are fitted with an adjustment screws (9) that limit the opening angle of cutting tool holders (7) during the drill string rotation. Cutting tools (10) are fixed at the lower part of the holder levers and have two cutting edges that secure vertical and lateral ice cutting. The cutting tools are designed with guards (11) that prevent the tool slapping in drilling.

The borehole reaming is done in the following way (Figure 4):

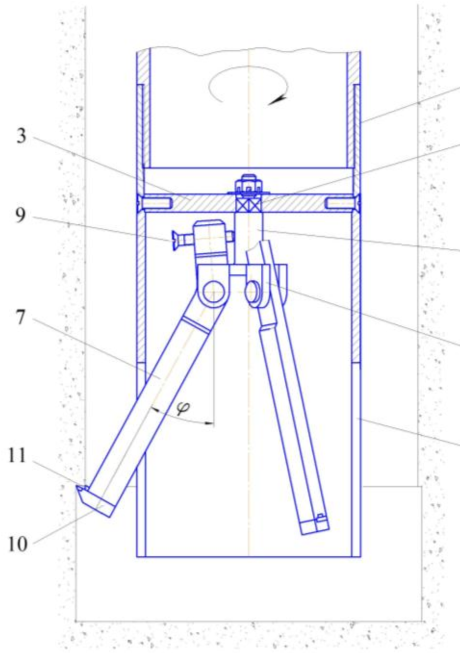


Figure 4. Mechanical inertial reamer in operating position

The reamer is fixed instead of the drill bit at the end of the drilling tube of the mechanical drilling assembly. Screws (9) are adjusted so as to reach the required opening angle of cutting tool holders (7). In transport position all the cutting tools are located inside housing (1).

The drilling assembly is run into the borehole until the bottom edge of housing (1) reaches the borehole bottom. Then, the drill sting rotation is started and the angular velocity of the reamer reaches ω = 13.6 – 23 c^{-1}. The resulting centrifugal inertial force makes cutting tool holders (7) deviate from the rotation axis by angle φ and extend out of housing (1) through axial slots (2) in the housing until cutting tools (10) rest against the borehole walls.

The borehole is reamed when the drilling assembly starts rotating and simultaneously lifting up the borehole. Once borehole reaming is completed, the drill string rotation is stopped. When this happens, cutting tool holders (7) are closed by the gravity force. The drilling assembly with the reamer can be pulled from the borehole.

Subsequently, reaming can be repeated with the adjustment screws (9) set to obtain the required opening angle of the cutting tools as consistent with the attained borehole diameter.

SIMULATION OF CUTTING TOOL HOLDER OPENING PROCESS

Simulation of the opening process for the cutting tool holders was performed in order to determine their mass-centering characteristics within the specified range of borehole diameters.

Figure 5 shows an analytical model of the inertial reamer.

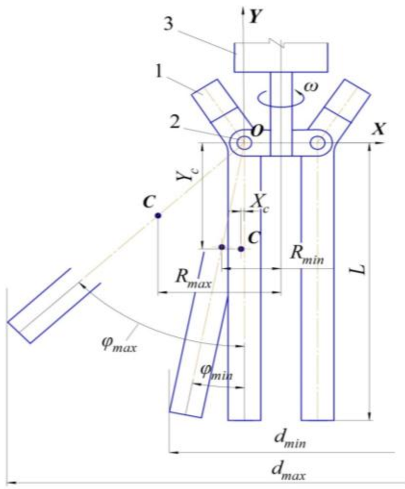


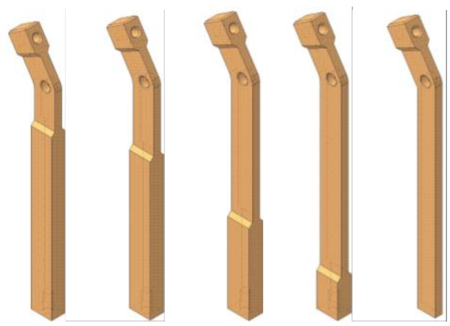
Figure 5. Analytical model of mechanical inertial reamer:
1 – cutting tool holder; 2 – axis of cutting tool holder;
3 – drill string

Dimensions and weights of the cutting tools were accounted for as part of the dimensions and weights of the cutting tool holders in creation of the analytical model and computer simulation.

The following designations are used in the model:

C – mass center of the cutting tool holder; φ_{min} – minimum defection angle of the cutting tool holder from the vertical axis, degrees; φ_{max} – maximum defection angle of the cutting tool holder from the vertical axis, degrees; R_{min} – distance from the drill string axis to the mass center of the cutting tool holder, corresponding to φ_{min}; R_{max} – distance from the drill string axis to the mass center of the cutting tool holder, corresponding to φ_{max}; *ω* – drill string rotation speed, c^{-1}; d_{min} – minimum borehole diameter, d_{min} = 138 мм; d_{max} – maximum borehole diameter, d_{max} = 300 mm; *L* – length of the cutting tool holder, mm.

Figure 6 demonstrates designs of the investigated cutting tool holders.



a) b) c) d) e)

Figure 6. Designs of cutting tool holder for the inertial reamer: a) Design 1; b) Design 2; c) Design 3; d) Design 4; e) Design 5.

When a cutting tool of the specified length touches the walls of a 138-mm borehole, the angle is 14º, while with a 300-mm borehole it will be 45º.

Defection of the cutting tool from the vertical axis takes place due to centrifugal inertial force $F_ц$ acting on the cutting tool holder while the reamer is rotating.

Figure 7 demonstrates a diagram of forces acting on the cutting tool due to the drill string rotation, axial feed force excluded.

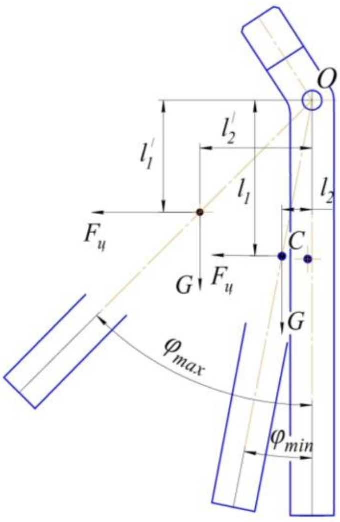


Figure 7. Diagram of forces acting on cutting tool

Five types of the cutting tool holder design have been considered (Figure 6). Material: structural steel with density ρ = 0.00782 g/mm^3.

Condition of cutting tool holder equilibrium in relation to center O (Figure 7)

$$\sum M_0 = F_ц l_1 - G l_2 = 0 \ ,$$

where l_1 and l_2 are arms of centrifugal inertial force $F_ц$ and gravity G, mm.

The following conditions should be met to secure opening of the cutting tool holders of the inertial reamer

$$F_ц \geq \frac{G l_2}{l_1} \ .$$

Thus, for instance, for the cutting tool holder design No.1 (Figure 6a) with length L of 170 mm, the value of centrifugal inertial force required to open the cutting tool holders shall exceed the following value:

at φ = 14^0, $F_ц \geq \frac{mgl_2}{l_1} = \frac{0{,}3 \cdot 9{,}8 \cdot 17}{71} = 0{,}70$ H;

at φ = 45^0, $F_ц \geq \frac{mgl_2^/}{l_1^/} = \frac{0{,}3 \cdot 9{,}8 \cdot 52}{52} = 2{,}94$ H.

For the drill string rotation speed ω = 23c^{-1}, the developed inertial force will equal:

at φ = 14^0, $F_ц = m\omega^2 R_{min} = 0{,}3 \cdot 23^2 \cdot 0{,}037 = 5{,}87$ H;

at φ = 45^0, $F_ц = m\omega^2 R_{max} = 0{,}3 \cdot 23^2 \cdot 0{,}072 = 11{,}43$ H.

For the drill string rotation speed ω = 13.6 c^{-1}, the developed inertial force will equal:

at φ = 14^0, $F_ц = m\omega^2 R_{min} = 0{,}3 \cdot 13{,}6^2 \cdot 0{,}037 = 2{,}05$ H;

at φ = 45^0, $F_ц = m\omega^2 R_{max} = 0{,}3 \cdot 13{,}6^2 \cdot 0{,}072 = 4{,}00$ H.

When this happens, the following opening angles are secured for the cutting tool holders:

at ω = 23c^{-1}

$$\varphi_{min} = \text{arctg}\frac{\omega^2 R_{min}}{g} = \text{arctg}\frac{23^2 \cdot 0{,}037}{9{,}8} = 1{,}106 \text{ rad;}$$

φ_{min} = 63.4^0.

$$\varphi_{max} = \text{arctg}\frac{\omega^2 R_{max}}{g} = \text{arctg}\frac{23^2 \cdot 0{,}072}{9{,}8} = 1{,}319 \text{ rad;}$$

φ_{max} = 75.6^0.

at ω = 13.6 c^{-1}

$$\varphi_{min} = \text{arctg}\frac{\omega^2 R_{min}}{g} = \text{arctg}\frac{13{,}6^2 \cdot 0{,}037}{9{,}8} = 0{,}609 \text{ rad;}$$

φ_{min} = 34.9^0.

$$\varphi_{max} = \text{arctg}\frac{\omega^2 R_{max}}{g} = \text{arctg}\frac{13{,}6^2 \cdot 0{,}072}{9{,}8} = 0{,}936 \text{ rad;}$$

φ_{max}= 53.6^0.

The obtained angle values are significantly higher than those required, thus, opening of the cutting tool holder of design No.1 and the length L of 170 mm is guaranteed for the given conditions.

Studies of the impact of the drill string rotation speed ω, weight m and length L of the cutting tool holder on the value of the developed inertial force $F_ц$ and opening angle φ were performed in order to determine the rational sizes of the cutting tool holders. The following lengths L of the cutting tool holders were considered: 170 mm, 190 mm, 210 mm, 240 mm, and 260 mm for all the design types shown in Figure 6.

The distance from the mass centers to the rotation axes R_{min}, R_{max} was determined using the solid-state computer simulation techniques for the cutting tool holders, the investigated weights and lengths, while a decrease in weight m was attained by keeping length L constant and changing the cutting tool holder design (Figjre 6).

The results of these studies for the cutting tool holder length L = 170 mm are shown in Figures 8 and 9.

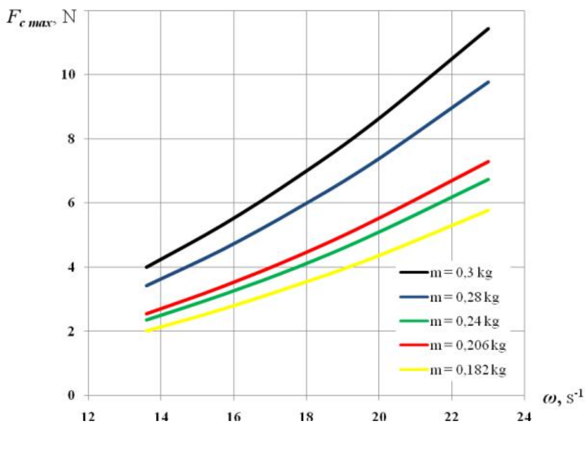


Figure 8. $F_{c\ max}$ = f (ω) dependence with account for cutting tool holder and cutting tool weights

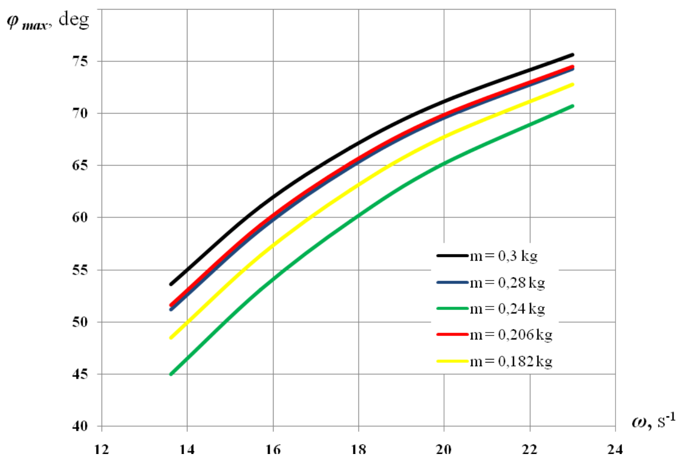


Figure 9. φ = f (ω) dependence with account for cutting tool holder and cutting tool weights

Analysis of the obtained results has shown that the values of the maximum centrifugal inertial force $F_{c\ max}$ and the maximum opening angle φ_{max} are significantly influenced not only by the weight of the cutting tool holder, but also by its design (See Figures 8 and 9).

The design and dimensions of the cutting tool holders were determined based on the performed research. A detailed design of the mechanical inertial reamer (Figures 10 and 11) was executed with replaceable cutting tool holders of two standard sizes: L = 170 mm, m = 0.3 kg and L = 240 mm, m = 0.42 kg, manufactured following the design shown in Figure 6a.

Figure 10. Inertial mechanical reamer

Figure 11. Design of the inertial mechanical reamer

A prototype model was made following this design.

CONCLUSIONS

The developed inertial mechanical reamer meets all the specified operating requirements:

- Simple design;
- Ease of assembly and disassembly from the drilling
- Diameter in the transport mode: 127 mm;
- Borehole reaming up to 300 mm;
- Secure arrangement to convert the reamer from the transport into the operating mode and backwards.

It stands to mention the design reliability of the arrangement used to convert the reamer from the transport into the operating mode and backwards. The suggested design totally eliminates the possibility of reamer jamming in the borehole.

The prototype model is planned to be tested at Vostok Station first using a test-bench and finally directly in Borehole 5G-3 during the seasonal shift period of the 62nd Russian Antarctic Expedition (from December 2016 till January 2017).

ACKNOWLEDGEMENTS

The logistic support for drilling operations at Vostok Station was provided by the Russian Antarctic Expedition. This work has been conducted with the support of the Russian Foundation for Basic Research, Project NK 14-05-93107\16.

The authors would like to express their deep gratitude to Galina V. Sokolova for his assistance in preparing this paper.

REFERENCES

[1] Lukin V.V. Put` k izucheniju vod ozera Vostok otkryt (Door to Study Waters of Vostok Lake is open) // Issues of Arctic and Antarctic. 2012. № 1(91). p. 5-19. [In Russian.]

[2] Antarktika. Geomorfologicheskiy Atlas (Antarctic. Geomorphological Atlas). St. Petersburg: "Karta" Publishing House, 2011. 255 p. [In Russian.]

[3] Masolov V.N., Popov S.V., Lukin V.V., Popkov *A.M.* Rel`ef dna i vodnoe telo podlednikovogo ozera Vostok, Vostochnaia Antarktida (Bottom Topography and Water Body of Vostok Subglacial Lake, East Antarctic) // DAN. 2010. P. 433. № 5. p. 693-698. [In Russian.]

[4] Leitchenkov G., Antonov A., Luneov P., Lipenkov V. 2016. Geology and environments of subglacial Lake Vostok. Phil. Trans. R. Soc. A. 2015. Vol. 373, 20140303. (doi: 10.1098/rsta. 2014.0303).

[5] N. I. Vasilev, A.V. Bolshunov, A.N. Dmitriev and A.V. Podoliak. Round-Trip Assembly for Investigations of Subglacial Lake Vostok. International Journal of Applied Engineering Research., Volume 11, Number 9 (2016), pp 6376-6380

[6] Kudryashov, B.B., V.K. Chistyakov and V.S. Litvinenko. 1991. Burenie skvazhin v usloviyah izmeneniya agregatnogo sostoyaniya gornih porod (Bore-hole drilling in the condition of rock aggregate changes). Leningrad, Nedra, 1-295. [In Russian.]

[7] Kudryashov, B.B., V.K. Chistyakov, V.A. Morev. 1983. Bureniye ledianogo pokrova Antarktidi teplovim sposobom. 25 let Sovetskoy Antarkticheskoy ekspeditsii. [Thermal drillingin Antarctic ice sheet. 25th Anniversary of the Soviet Antarctic Expedition.] L. Gidrometeoizdat. 149-158. [In Russian.]

[8] Lukin, V.V. and N.I. Vasiliev, Technological aspects of the final phase of drilling borehole 5G and unsealing Vostok Subglacial Lake, East Antarctica. Annal. Glaciol., 55(65). 83 –89.

[9] Pashkevich, V.M. and V.K. Chistyakov, 1989. Obespechenie ustoychivosti stvola skvazhini pri glubokom burenii v lednikovih pokrovah (Ensuring of bore-hole shaft stability when deep drilling in the ice covers). Antarktika (The Antarctic), 28. 39-50. [In Russian.]