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INSTRUMENTS AND METHODS

Diving Methods of Oceanologic Research

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Abstract—The article discusses advanced technologies, methods, and techniques of diving, which, according to the results of comparative testing, are most suitable for use in in situ oceanographic research by scientific divers, including oceanographers themselves with professional diving training. At the same time, a wider range of scientific problems are being solved, and the methodical level, efficiency, and quality of ocean research are being improved. For diving for scientific purposes, the most suitable method is short-term autonomous dives using breathing apparatus with a closed cycle of breathing gas mixtures with electronic adjustment of the composition of mixtures and diving technology using oxygen–nitrogen mixtures. These technologies can be a priority for further development and implementation in ocean research.

Keywords: diving research methods, diving methods, autonomous dives, breathing apparatus, breathing mixtures, efficiency of diving technologies

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One way to study the ocean is using diving technologies, which include physiological and technical diving methods of diving to conduct oceanographic research underwater. This scientific and technological direction greatly contributes to the development of innovative potential in the field of ocean research and the solution of fundamental problems of oceanology.

Unlike technical controlled systems (unmanned underwater vehicles and robots), a diver can solve assigned tasks underwater not only according to a given program, but also according to the situation. This is in situ research, which is an important condition for obtaining correct scientific information. Of course, the diving depth and work of the researcher on the seafloor is limited by his physiological capabilities and methods and modes of diving, mainly associated with breathing in a modified gas environment under the influence of increased pressure (hyperbaria). It is known that the work of a diver underwater or in a pressure chamber under the pressure of the respiratory gas environment leads to pronounced changes in all physiological systems of the body [2, 5, 7]. This requires more careful selection or the development of special diving methods for scientific purposes, because a diver-researcher (oceanologist) may have professional diving training, but the level of his professionalism, for obvious reasons, cannot be high.

With the modern development of methods, technical means of diving ad ensuring diving descents, the high efficiency of underwater research extends at least to the depths of the continental shelf. Therefore, oceanographers pay the greatest attention to topical problems of physics, geology, and biology of the ocean in the shelf zone [1]. The main tasks of oceanology, in the solution of which the use of diving methods in combination with other technical means is expedient, are currently focused mainly on the problems of ecology and bottom oceanology of the shelf. The experience of specialists in studying the shelf zone of inland seas and the World Ocean shows that bottom research without diving methods is deficient. Problems beyond the capabilities of underwater vehicles and robots remain unsolved, requiring experiments underwater, precision sampling, and regular sampling, and their counting by divers-researchers in situ. The use of diving methods in surveying an area of the ocean floor accessible to humans will make it possible to study the state of the bottom and processes occurring at the water–bottom interface, where the ecological conditions of the shelf zone are largely formed.

In addition, underwater, and especially near-bottom, research requires the installation at a given place of the bottom of scientific instruments, including sediment traps, requiring monitoring of work on currents, inspection of the integrity and safety of installed and submerged objects, underwater photography and video recording, etc.

Obviously, diving methods for scientific research are most effective in underwater biological and chemical studies. This is because raising to the surface various samples, specimens and living organisms from depth, even with special devices, leads to their biochemical and physicochemical transformation.

When samples and living organisms are raised to study them on the surface, the pressure, temperature, and other physical parameters of the aquatic environment change, which leads to inevitable shifts in their structure up to tissue damage.

Therefore, scientific research of seafloor objects should ideally be carried out in situ with special underwater equipment used by a trained diver or scientist with professional diving training and experience underwater [11, 12]. The relevance of the use and development of diving methods for studying the ocean seems obvious, since this solves a wider range of scientific problems and increases the methodological level, efficiency and quality of oceanographic research. This article discusses the technologies, methods and techniques of diving since, which, according to the results of comparative testing, are suitable for practical use, since they are efficient in conducting underwater research.

During diving descents and operations, methods of studying the efficiency and suitability were used: comparative testing and assessment of diving techniques in Black Sea waters to medium (up to 60 m) depths, and analysis and assessment of technologies and diving techniques based on surveys and the results of performing tasks underwater. During descents, SCUBA gear with open and closed breathing cycles were used. Diving descents were carried out under the supervision and with the participation of a diving specialist S.V. Cherkashin.

Modern diving technologies are based on two methods: short-term dives (STD) and long stay (LS) under high pressure. They differ as followings: during STD, bodily tissues are partially saturated with an inert gas; therefore the decompression time depends on the residence time at a given depth. During LS, bodily tissues are completely saturated with an inert gas. In this case, the decompression time does not depend on the residence time at a given elevated pressure. These methods are based on the physiological principles of constructing a technique for descending to depth (compression), working on the ground (working capacity), and ascent to the surface (decompression) [11]. The safety of the entire diving cycle depends on strict adherence to these.

It should be noted that at present, the LS method is barely used in global research practice due to the high cost of organizing and ensuring a long residence time under high pressure in the pressure chambers of the ship's diving complex and scientific work underwater, although its efficiency is recognized as the highest.

The STD method for scientific diving is gaining great importance due to the development and implementation of high-tech and reliable diving equipment (breathing apparatus), which is promising for use in underwater research even, under certain conditions, by oceanographers themselves. Currently, three main types of diving equipment can be distinguished, regardless of the purpose of their use, which prevail in the domestic practice of diving descents and operations at medium and partly at great depths:

—breathing apparatus with an open breathing cycle (OCR) for breathing compressed air and gas mixtures when descending to a depth of up to 60 m;

—breathing apparatus of various modifications with closed-cycle breathing (CCR) gas mixtures for autonomous descents to depths of approximately 100 m;

—air-ventilated hose equipment (diving suit with helmet) for descents to depths of up to 60 m.

The hose-type equipment, including hose-type breathing apparatus, are not popular in scientific descents because they impede the diver's mobility underwater, which is important for research. Compressed air open-cycle (OCR) devices are the subject of comparative analysis only, excluding targeted studies. This is a classic piece of equipment that has undergone extensive testing for decades, which is still successfully used in solving many problems, including scientific ones, at shallow depths and during limited time underwater. Diving to great depths (over 60 m) using apparatus with an open breathing cycle is impractical due to the high consumption of respiratory gas mixtures (RGM) and the need to carry additional cylinders with breathing mixtures, therefore, such descents for scientific purposes are unpromising.

Among the modern systems with a closed breathing cycle, the most promising are the so-called "mixed" apparatuses with electronic regulation of the composition of the respiratory mixture and maintaining a constant level of partial pressure of oxygen (PO_2) regardless of depth. The results of autonomous diving trips using such devices (Fig. 1) showed that this technique is the most efficient, cost-effective and relatively safe for oceanologic research.

This is a new and progressive method of diving for scientific purposes, which can also be considered a technology that allows a diver, when using breathing mixtures, to work in the zone of deep-water descents, that is, at depths over 60 m according to the Russian depth gradation. If special safety requirements are met and work experience is available, such devices can operate at depths of up to 100 meters or more, but the time spent on the seafloor is severely limited by the need for prolonged decompression in water, so the effectiveness of such descents is low [9]. However, at medium depths, this technique is effective and has great advantages over traditional descents, since it ensures performance of scientific, industrial, and search and rescue tasks, including special tasks aimed at carrying out confidential missions underwater [8, 10].

The main organizational and economic advantages of the autonomous method include the following:

—high autonomy and mobility;

—the ability to work from almost any floating craft, as well as from shore and from underwater carriers with systems for entering the water such as "Lock Out";

Fig. 1. Diver before descent in autonomous mode (left) and work on seafloor (right) (photo from archive of S.V. Cherkashin).

—low gas consumption for one filling of the apparatus, sufficient for 3 h of breathing underwater;

—comparatively low cost of diving and operations within average depths in comparison with works carried out by traditional STD methods.

The main purpose of using this STD method in standalone mode (STDSM) is to increase the efficiency of underwater research on the bottom. In this regard, "mixed" apparatuses based on a closed breathing cycle (rebreather) and electronic regulation of the composition of the breathing mixture are best suited for solving scientific problems underwater. These are the most technically advanced devices. Of these, the Inspiration and Evolution devices (AP Diving-Great Britain) presented on the Russian market, as well as domestic ones, of which the new device of AV Underwater Technologies BRIZ (CCR BRIZ) should be distinguished. Due to modern electronics, such devices increase their functionality. This provides operational control of rebreather parameters, such as, for example, the selection of the set pressure and maintaining a constant PO_2 value at depths, its automatic switching at a given depth horizon, the calculation of the decompression mode in real time, alarms about exceeding the values of safe parameters, and others. In such devices, for the formation of RGM, air is usually used as a diluent of the mixture at medium depths. At greater depths, the mixtures are preferable based on nitrogen and helium (trimix) or on helium (heliox) in specified ratios, depending on the depth range.

The implementation of this technology, based on the principle of rebreathing, makes it possible to solve many problems necessary for underwater research. The multifunctionality of the "mixed" devices under certain conditions provides:

—increase in operating time at a depth (up to 3–4 h at one filling with a mixture, regardless of depth);

—expanding the range of operating depths;

—the use and variation of respiratory gas mixtures of different composition during descent are the main advantages of the method and device;

—minimizing decompression time;

—increasing the comfort level of a diver's breathing (because of a chemical reaction in the cartridge of the CO_2 absorber, the gas mixture enters the breathing heated and humidified).

To introduce this technology into research practice during diving descents, the following is necessary:

—to master reliable computer programs for calculating the diving mode, including the decompression regime, considering the composition of the RGM used;

—to develop of the training and education system for divers, including the scientists.

The most difficult problem in implementing this technique is decompression. Without solving this problem, diving descents are unsafe. This problem is that the decompression tables for traditional descents are designed for breathing with a single mixture (air or an oxygen–nitrogen mixture) and do not consider the possibility of switching to breathing with different breathing mixtures during the entire cycle of the diver's descent-ascent to the surface. However, computer programs for calculating decompression modes make it possible to apply the advantages of using various mixtures and their effective variation, thereby minimizing decompression and other physiological disorders.

To improve the efficiency and safety of diving descents to medium and large depths by the STDSM method, it becomes necessary to use RGM of different compositions at different depths. This is strictly related to the need to maintain the level of PO_2 (1.4–1.6 kgf/cm^2) and nitrogen (4–5 kgf/cm^2) within safe limits. Depending on the range of working depths for a given dive, up to four or more mixtures can be used to optimize the general descent mode: pure oxygen, air, various nitrogen–oxygen (Nitrox), helium–oxygen (Heliox), helium–nitrogen–oxygen (Trimix) and helium–air mixtures (HeliAir).

When descending in autonomous mode, all decompression usually takes place in the water, that is, without going to the surface, therefore the total duration of stay underwater is one of the factors limiting the dive. To reduce the time of decompression stops, the RGM is changed more often than with conven-

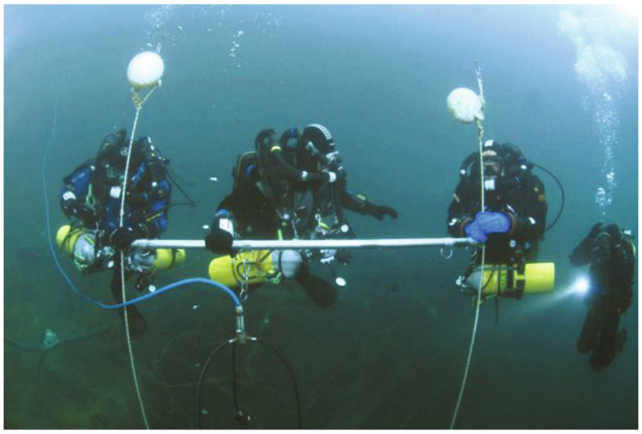

Fig. 2. Divers in decompression stop after autonomous descent (photo from archive of S.V. Cherkashin).

tional descents using the STD method. This has a positive effect on pulmonary gas exchange, which reduces the likelihood of decompression disorders in a diver.

Modern devices operating in a closed breathing circuit have a high level of reliability, so they are especially promising for divers-researchers, which is directly related to their safety. World experience in the effective use of such devices allows us to recognize the advantages of closed (recirculating) systems (CCR) over devices with an open breathing circuit (OCR) for scientific dives.

A striking example of the effectiveness of a “mixed” apparatus with a closed breathing cycle is an approximately twofold increase in the time spent underwater at medium depths, after which there is no need for step decompression. It does this by optimizing the composition of the breathing gas underwater. An even greater effect is observed in relation to the decompression time, which is more than halved after staying at depths of up to about 50 m compared to breathing from an apparatus with an open breathing cycle with compressed air.

RGM consumption when using a rebreather is also important. When breathing underwater at a constant depth, there is no mixture flow at all working depths, because the breathing circuit is closed, there is no release of the exhaled mixture into the water. Inert gas (nitrogen, helium) is not consumed during breathing, and the oxygen consumed by the body is replenished from a standard cylinder.

Thus, the approbation of the autonomous mode descent technique (Fig. 2) convinces of its high efficiency when using “mixed” devices with a closed breathing cycle in the entire range of depths and underwater research accessible to a scientific diver. This is especially evident in the range of average depths (30–60 m).

The high autonomy and no need for support from the surface make this method as mobile as possible, economically and scientifically more effective in a wide range of underwater operations, which sporadic in nature, typical of oceanographic research. The absence of gas bubbles when exhaling and silence when breathing underwater is a big plus for research when monitoring underwater fauna.

The specific features of autonomous diving place special demands on the training of divers-researchers It should be admitted that at present the technology and methodology of diving for scientific purposes by the STDSM method have not yet been sufficiently developed. There is no normative and regulatory documentation for descents and research work on the seafloor. The main principles of organizing and conducting descents are still diving experience, research skills of working underwater and the diver’s personal responsibility for the safety of the descent. But this does not limit the difficulties associated with the use of “mixed” devices based on a closed breathing cycle. The fact is that when descending with such devices, decompression, as noted above, is carried out in accordance with the calculated decompression modes using a dive computer, and not according to standard tables. Such a feature of descents at this stage of the development of the technique requires underwater control of the state of a research diver, especially when the latter belongs scientist, which in its significance exceeds his personal responsibility.

A simpler, but no less effective technology for performing diving operations in an autonomous mode is the use of oxygen-enriched breathing mixtures in a breathing apparatus instead of compressed air. The oxygen content in the mixture is selected depending on the depth of the dive.

These mixtures can be oxygen–nitrogen (ONM), air–helium (AHM), and oxygen–nitrogen–helium (ONHM) mixtures.

Breathing mixtures based on helium and nitrogen, especially ONHM, are more difficult to prepare. In addition, the cost of helium and a breathing apparatus for helium-containing mixtures significantly limits their practical use, although such mixtures are more comfortable for breathing and allow the diver to work at great depths. Therefore, at this stage in developing of diving technology for scientific purposes, it is advisable to limit oneself to descents using ONM with an oxygen content of up to 40%.

The main principle of ensuring greater efficiency of diving descents using ONM is to increase (with respect to air) the oxygen content in the RGM within the nontoxic zone (considering the duration of breathing at depth) and thereby reduce the nitrogen content.

The use of ONM in practice significantly increases the efficiency of diving descents and research work at shallow (up to 12 m) and medium (at least up to 45 m) depths. Such mixtures have clear advantages over compressed air. This is reflected in the increased depth and duration of scientific work underwater without decompression. For example, the duration of decompression after 35 min of work underwater when breathing air at a depth of 35 m is 43 min, and when breathing ONM with a 40% oxygen content, 3 min (time of surfacing) [3]. With this technology, the body's saturation with nitrogen decreases due to its lower content in the respiratory mixture, and therefore the decompression time is reduced. The fact is that when breathing an oxygen-enriched mixture at depth, the equivalent calculated "air" depth conditionally decreases due to a decrease in the nitrogen content; therefore, the decompression time from this depth is reduced. Decompression after descent to a depth of 35 m and work on the seafloor for 90 min while breathing compressed air is 2 h 42 min, and when breathing ONM with 40% oxygen, the decompression time is reduced to 1 h 05 min, i.e., more than twice. It is important that when breathing a hyperoxic mixture, nitrogen anesthesia is minimized and it disappears at shallow depths due to a decrease in the nitrogen content in the respiratory ONM. And most importantly, physical performance underwater is maintained due to the increased oxygen content in the respiratory mixture. Such efficiency of breathing underwater with ONM is an example of successful use of the physiological principles of this technology [13].

When using ONM, in any case, the amount of nitrogen dissolved in tissues will be less than when breathing air, which reduces the risk of decompression sickness.

Breathing a 40% ONM eliminates the need for gradual decompression when working at depths of up to 30 m for up to 45 min. By reducing the operating time on the seafloor, the no-decompression depth can be increased to 45 m. In terms of both time and depth, this is quite sufficient to fulfill many tasks in oceanological research. It should be noted that this technology is fundamentally different in technical terms from the above. Structurally, the breathing devices have almost nothing in common, but the efficiency of each of these technologies is nearly equally high. However, the readiness of the ONM-based technology for implementation in oceanological research is only at the initial stage. There is no regulatory documentation on labor protection during underwater research, there are no special breathing devices for using them with oxygen-nitrogen mixtures, the problems of preparation and control of mixtures in the apparatus cylinders have not been solved, the decompression modes after work underwater have not been tested, although they are calculated, depending on the oxygen content in RGM. Despite the high efficiency of this technology, it requires increased monitoring of the condition of the diver underwater, which is associated with the risk of developing the toxic effect of oxygen on the body [4, 6]. In addition, the implementation of this technology is associated with a high level of requirements for the safety of work with the use and preparation of ONM.

The development of physiological and technical requirements for the organization of descents and the work of a scientific diver underwater is of great importance for the development and implementation of this technology. It is also important to develop new breathing gas mixtures to improve the safety and efficiency of performing scientific tasks underwater, as well as to develop special diving breathing devices and diving computers (decompression meters) to work with ONM and other technical means necessary for diving descents.

Thus, the results of comparative testing and analysis of the scientific efficiency of diving in an autonomous mode showed that the technology and methodology of using the hardware with a closed breathing cycle of the "rebreather" type is suitable, effective and promising in in situ oceanological research. Closed-cycle "mixed" apparatuses are efficient in the entire range of working depths up to 100 m. But only professional divers can work at great depths.

The technology of autonomous diving using ONM for breathing is also suitable, efficient, and promising for use in oceanographic research. In some aspects, this technology may be even more effective than closed-circuit breathing apparatus, because in a certain range of depths and underwater operating times, the decompression mode is eliminated or minimized because saturation of the body with nitrogen is reduced due to its lower content in the breathing mixture. In addition, nitrogen narcosis is relieved by lowering the nitrogen content in the respiratory ONM. And what is especially important, physical performance underwater is maintained due to the increased oxygen content in the breathing mixture. However, the prospect of introducing this technology is still rather far off for use in research due to some of the above-mentioned unsolved problems.

To introduce diving methods into oceanographic research, it is advisable to create a mobile diving group and equip it with modern breathing apparatus that make it possible to use the advantage of breathing underwater with various gas mixtures, as well as other equipment that allows diving for scientific purposes. It is advisable to limit to 30–40 m the depth for divers from among scientific personnel, regardless of the considered diving technologies and depending on the qualifications, experience, conditions, and tasks of diving, without changing the RGM and preferably with no decompression modes.

The conditions of descent, the specifics of the bottom relief, and peculiarities of the natural factors of the aquatic environment in different oceanic regions entail different technical and methodological approaches to organizing and performing underwater research, thereby requiring, in addition to basic diver training, various research specializations making it possible to conduct scientific research in marine biology, geology, physics, and other fields.

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